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Estimating crop coefficients from fraction of ground cover and height

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Abstract The FAO-56 procedure for estimating the crop coefficient K_c as a function of fraction of ground cover and crop height has been formalized in this study using a density coefficient K_d. The density coefficient is multiplied by a basal K_c representing full cover conditions, $K_{cb\ full}$, to produce a basal crop coefficient that represents actual conditions of ET and vegetation coverage when the soil surface is dry. $K_{cb\ full}$ is estimated primarily as a function of crop height. $K_{cb\ full}$ can be adjusted for tree crops by multiplying by a reduction factor (F_r) estimated using a mean leaf stomatal resistance term. The estimate for basal crop coefficient, K_{cb}, is further modified for tree crops if some type of ground-cover exists understory or between trees. The single (mean) crop coefficient is similarly estimated and is adjusted using a K_{soil} coefficient that represents background evaporation from wet soil. The K_c estimation procedure was applied to the development periods for seven vegetable crops grown in California. The average root mean square error between estimated and measured K_c was 0.13. The K_c estimation procedure was also used to estimate K_c during midseason periods of horticultural crops (trees and vines) reported in the literature. Values for mean leaf stomatal resistance and the F_r reduction factor were derived that explain the literature K_c values and that provide a consistent means to estimate K_c over a broad range of fraction of ground cover.

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Introduction

The two-step crop coefficient (K_c) × reference evapotranspiration (ET_{ref}) method has been a successful and dependable means to estimate evapotranspiration (ET) and crop water requirements. The method utilizes weather data to estimate ET for a reference condition and multiplies that estimate by a crop coefficient that represents the relative rate of ET from a specific crop and condition to that of the reference. The reference condition is generally ET from a clipped, cool season, well-watered grass (ET_o) or from a taller full-cover alfalfa crop (ET_r). The calculation of ET from these surfaces has been standardized by FAO (Allen et al. 1998, 2006) and the American Society of Civil Engineers (ASCE-EWRI 2005).

The K_c ET_{ref} approach provides a simple, convenient and reproducible way to estimate ET from a variety of crops and climatic conditions (Doorenbos and Pruitt 1977; Wright 1982; Snyder et al. 1989a, b; Allen et al. 1998). Developed K_c curves or values represent the ratios of $ET_{c.}$ to ET_{ref} during various growth stages. Crop coefficient values have been reported for a wide range of agricultural crops (Allen et al. 1998, 2007a). The K_c is regarded as generally transferable among regions and climates under the assumption that the ET_{ref} accounts for nearly all variation caused by weather and climate. Therefore, the K_c represents the relative fraction of ET_{ref}, and is chiefly governed by the amount, type and condition of vegetation. Vegetation characteristics are more consistent for agricultural vegetation than for natural vegetation. Tabular values for K_c are often successfully used over a wide range of agricultural applications. Transferability of K_c values is supported, in the case of the grass reference ET, by an equation that adjusts tabularized K_c to climate as a function of daily minimum relative humidity, wind speed, and crop height (Allen et al. 1998).

Conversely, the vegetation amount, height, and density of many systems, including natural vegetation, orchards, and residential and rural landscapes, is highly variable, even during the middle part of the growing season, so that substantial uncertainties exist with tabularized values for these systems. Under these conditions, K_c values can be more accurately estimated by basing the estimates on the fraction of ground covered or shaded by vegetation, the height of the vegetation, and the amount of stomatal regulation under moist soil conditions. The value for K_c for conditions of low soil water availability is generally determined by reducing the K_c estimate via K_s using a daily soil water balance model.

This paper describes a relatively simple approach for estimating the K_c value based on a physical description of the vegetation. The method traces to the FAO-56 publication (Allen et al. 1998) with extensions made to account for background evaporation from soil and better seamlessness of the procedure. The procedure is intended for estimating both basal and average K_c for natural vegetation, orchards and landscape systems for different portions of the growing season based on amount of vegetation present and background evaporation from soil.

Background

Basal crop coefficient

Basal crop coefficients, K_{cb}, represent primarily the transpiration component of ET and a small evaporation component from soil that is visibly dry at the surface. The use of K_{cb} over long periods requires adjustment for evaporation from wet soil during periods following rain or irrigation. The total crop coefficient, K_c is computed from K_{cb} as:

$$K_c = K_s K_{cb} + K_e \quad (1)$$

where K_s is a dimensionless 'stress' coefficient whose value is dependent on available soil water and K_e is a coefficient that adjusts for increased evaporation from wet soil following rain or irrigation. The procedure in Eq. 1 has been referred to as the 'dual' K_c approach (Allen et al. 1998, 2005a). The values for K_e create "spikes" in the K_c curve as shown in Fig. 1. Estimation of K_e for bare soil conditions is described in Wright (1982) and Allen et al. (1998, 2005a, b). The value for K_s is 1 unless available soil water limits transpiration, in which case it has a value less than 1. Calculation of K_s (and K_e) requires a daily soil water balance as described in Allen et al. (1998, 2005a, 2007a) and Cholpankulov et al. (2008) and the specification of a shape function for K_s versus soil water content or soil water potential. The value specified for the soil water threshold at which water stress begins does impact the K_c estimation and may need to be determined locally (Popova et al. 2006; Raes et al. 2009).

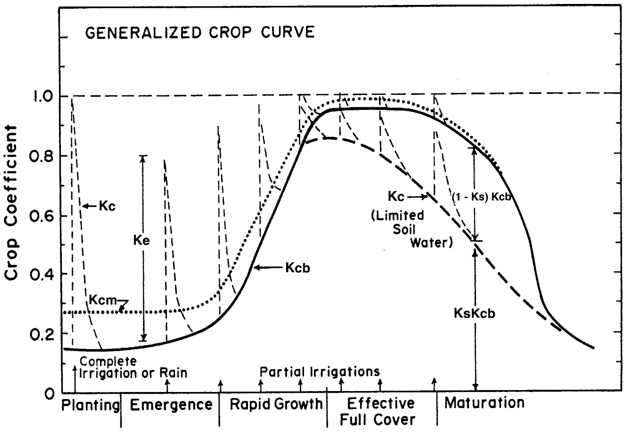

Fig. 1 Generalized crop coefficient curves, K_c, for an annual field crop over a growing season showing the effects of increasing K_c during midseason caused by plant development (K_{cb}), wet soil surface (K_e) and (*long-dashed curve*) limited available soil water ($K_s K_{cb}$). K_{cm} is the single K_c representing averaged evaporation effects (after Wright 1982; Jensen et al. 1990)

Single crop coefficients

In basin-wide water balance studies or irrigation systems planning, use of 'single' crop coefficients that imbed averaged effects of evaporation from wet soil are more useful and convenient than computing a daily K_c based on K_{cb}, K_s, and K_e. The single crop curve, K_{cm}, shown in Fig. 1 lies above the basal curve by an amount that depends on the frequency of soil wetting. The K_{cm} is in essence a 'time-averaged' K_c as opposed to the 'dual K_c'. When a single crop coefficient is used, usually no additional adjustment is made for the effects of surface soil wetness. Adjustments are made for the effects of limited soil water as:

$$K_c = K_s K_{cm} \quad (2)$$

Values for K_{cm} during partial crop cover depend not only on the amount and type of vegetation cover, but also on frequency of precipitation and irrigation and whether irrigation wets all or part of the soil surface. K_{cm} curves can be generated from K_{cb} curves for known or simulated precipitation or irrigation frequencies following the dual K_{cb} approach and daily timestep.

Segmented crop coefficient curves

Figure 1 shows realistic K_c curves that have smooth, continuous transitions during the growing season. K_c curves have often been constructed, for simplicity in construction and estimation, using the FAO segmented approach shown in Fig. 2 where the continuous seasonal curve is broken

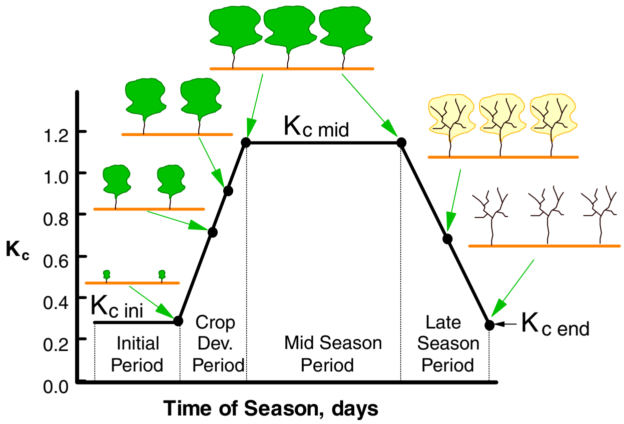

Fig. 2 FAO segmented crop coefficient curve and four growing stages (after Allen et al. 1998)

into four linear segments representing the initial, development, midseason, and late season periods (Doorenbos and Pruitt 1977; Allen et al. 1998, 2005a). The appeal of the FAO style curve is that only three key values for K_c need to be determined: $K_{c\ ini}$ during the initial period, $K_{c\ mid}$ during the midseason period, and $K_{c\ end}$ at the end if the late season period. Values for $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ are listed in FAO-56 (Allen et al. 1998, 2007a). The FAO style curve can be applied equally well to basal and single K_c applications in both dual and single mode. Examples of application of the FAO style K_{cb} curves in a dual K_c model include Hunsaker (1999), Tolk and Howell (2001), de Medeiros et al. (2001), Ringersma and Sikking (2001), Hunsaker et al. (2002, 2003, 2005), Pereira et al. (2003), Howell et al. (2004), Mutziger et al. (2005), Allen et al. (2005a, 2007a), Paço et al. (2006), Spohrer et al. (2006), Rolim et al. (2006), Kato and Kamichika (2006), Goodwin et al. (2006), Zhao and Nan (2007), Bodner et al. (2007), Er-Raki et al. (2007), López-Urrea et al. (2009a, b, c), Greenwood et al. (2009), and Yang et al. (2009).

The procedures for constructing K_c curves presented in the following apply to both grass and alfalfa reference bases. Therefore, distinction is made between those K_c values that apply to grass reference and those that apply to the alfalfa reference by denoting the former as K_{co} and the latter as K_{cr}. The two types of K_c's should not be interchanged, because K_{co} is generally 20–30% larger than K_{cr}. The larger values for K_{co} are required because ET_o tends to be 20–40% smaller than ET_r.

Adjusting K_{co} for climate

The ratio of $ET_{c.}$ to grass ET_o for many crops increases as wind speed increases and as minimum daily relative humidity decreases (Doorenbos and Pruitt 1977). This is due primarily to differences in roughness between taller agricultural crops and the clipped grass reference. The result is a higher K_{co} value caused by increased roughness and perhaps leaf area making the aerodynamic aspects of vapor transport more important and significant. The adjustment to K_{co} is generally required only for coefficients based on the grass ET_o reference. No adjustment for climate is necessary for coefficients based on the alfalfa ET_r reference because of the greater roughness of alfalfa that is more similar to most crops (Wright 1982; Pereira et al. 1999). The FAO procedure for adjusting K_{co} values uses mean daily minimum relative humidity and wind speed. For climates with RH_{min} greater than or less than 45% or with mean wind speeds at 2 m over grass (u_2) that are more than or less than 2.0 m s^{-1}, the standardized values for all $K_{co\ mid}$ and $K_{cbo\ mid}$ from FAO-56 and for $K_{co\ end}$ and $K_{cbo\ end} > 0.4$ are adjusted as:

$$K_{co\,mid/end} = K_{co\,mid/end(table)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \qquad (3)$$

where $K_{co\ mid/end(table)}$ is the value for $K_{co\ mid}$, $K_{cbo\ mid}$, $K_{co\ end}$ or $K_{cbo\ end}$ for the standardized climate and h is the mean maximum plant height (m) during the midseason period, or full cover period. Equation 3 is valid for $h < 20$ m (Allen et al. 1998, 2005a). The values for RH_{min} and u_2 need only be approximate values averaged over the midseason and late season periods.

Estimating K_c curves from fraction of ground cover

Natural vegetation systems tend to have extensive variability in vegetation density, plant height, and water availability, both within a single expanse and between expanses of the same vegetation. Therefore, the distribution of K_c and thus ET populations can be broad, as shown in Fig. 3, where a frequency distribution of ET for the month of June and calendar year for cottonwood and salt cedar populations along a 100-km stretch of the Middle Rio Grande valley is shown as derived from satellite-based energy balance (Allen et al. 2007b). ET from salt cedar showed larger variance due to its tendency to grow across a broad range of water availability (water table depth), soil types, and salinity conditions, whereas cottonwoods, which exhibited a smaller variance in the population of ET, are typically found close to stream channels and consistent water supply. Wide variation was also noted for tree population density, which added to variance in the populations of ET.

For expanses of vegetation large enough that an equilibrium boundary layer is established so that general one-dimensional equations such as the Penman–Monteith apply, a maximum upper limit on ET is established due to the law of

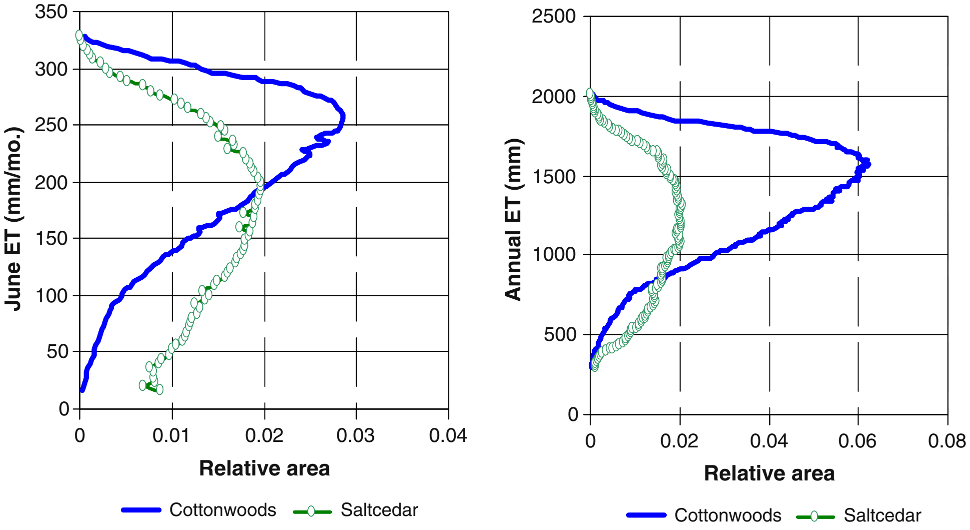

Fig. 3 Frequency distributions of ET from 6,000 ha of cottonwood and salt cedar along the Middle Rio Grande in New Mexico during June and all of 2002

conservation of energy. Therefore, for large expanses of vegetation (larger than about 500–2,000 m^2), the K_c development process has upper limits for K_{cr} of about 1.1 for the alfalfa reference and upper limits for K_{co} of about 1.3 for the grass reference. K_c's for smaller expanses (<500 m^2) should also adhere to these limits when the vegetation height and leaf area is less than or equal to that of surrounding vegetation and soil water availability is similar. Only 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) will peak K_c's exceed the limits stated. The user should exercise caution when extrapolating ET measurements from small vegetation stands or plots to large stands or regions, as overestimation of ET may occur.

The upper, energy-constrained limit on K_c can be used to advantage in estimating K_c for vegetation for which the K_c is unknown, by using it to set the upper limit for vegetation having full or nearly full ground cover. This upper limit, termed $K_{c\ max}$ is defined as the maximum value for K_c following rain or irrigation. The value for $K_{c\ max}$ is governed by the amount of energy available for evaporation of water, which is largely encapsulated in ET$_{ref}$. As with the case of K_{co}, the $K_{c\ max}$ used with ET$_o$ varies with general climate, ranging from about 1.05 to 1.30 (Allen et al. 1998, 2005a):

$$K_{c\ max\ o} = \max\left(\left\{1.2 + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right\}, \left\{K_{cbo} + 0.05\right\}\right) \qquad (4a)$$

where u_2 is average wind speed at 2 m during the particular growth stage or period, RH$_{min}$ is average daily minimum relative humidity during the growth state or period and h is the mean plant height (m) during the period of calculation (initial, development, midseason, or late-season). The K_{cbo} denotes a basal K_{cb} used with ET$_o$ estimated in a later section.

$K_{c\ max}$ for the tall reference ET$_r$, denoted as $K_{c\ max\ r}$, does not require adjustment for climate, due to the greater roughness of the alfalfa reference basis:

$$K_{c\ max\ r} = \max(1.0, \{K_{cbr} + 0.05\}) \qquad (4b)$$

where K_{cbr} denotes a basal K_{cb} used with ET$_r$. Equations 4a and 4b require that $K_{c\ max}$ is greater than or equal to the sum K_{cb} + 0.05, suggesting that wet soil increases the K_c value above K_{cb} by at least 0.05 following complete wetting of the soil surface, even during periods of full ground cover.

The value for K_c reduces when plant density or leaf area fall below full ground cover which, in some cases, has been defined as when leaf area index LAI < 3. Because the K_c tends to decrease in proportion to the amount of vegetation, the basal K_{cb}, which correlates with amount of vegetation because it represents mostly transpiration, can be expressed in terms of a density coefficient, K_d, where:

$$K_{cb} = K_{c\ min} + K_d(K_{cb\ full} - K_{c\ min}) \qquad (5a)$$

where K_{cb} is the approximation for K_{cb} 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 ($K_{cb\ min}$ ~0.15 under typical agricultural conditions and $K_{cb\ min}$ 0.0–0.15 for native vegetation, depending on rainfall frequency). The density coefficient K_d can be estimated as a function of measured or estimated leaf area index LAI or as a function of fraction of ground covered by vegetation. The density coefficient is defined in Eq. 9.

For tree crops having grass or other ground cover, Eq. 5a can take the form:

$$K_{\mathrm{cb}} = K_{\mathrm{cb\ cover}} + K_{\mathrm{d}}\left(\max\left[K_{\mathrm{cb\ full}} - K_{\mathrm{cb\ cover}}, \frac{K_{\mathrm{cb\ full}} - K_{\mathrm{cb\ cover}}}{2}\right]\right) \tag{5b}$$

where $K_{\mathrm{cb\ cover}}$ is the K_{cb} of the ground cover in the absence of tree foliage. The second term of the max function reduces the estimate for $K_{\mathrm{cb\ mid}}$ by half the difference between $K_{\mathrm{cb\ full}}$ and $K_{\mathrm{cb\ cover}}$ when this difference is negative. This accounts for impacts of the shading of the surface cover by overstory vegetation having K_{cb} that is lower than that of the surface cover due to differences in stomatal conductance. Equations 5a and 5b can be applied to estimate K_{cb} during any period, including the midseason period. The value for K_{cb} from Eq. 5a and 5b should be applied as a basal coefficient using the dual $K_{\mathrm{cb}} + K_{\mathrm{e}}$ method, since the actual K_{c} may increase to 1.0 for $\mathrm{ET_r}$ or 1.2 for $\mathrm{ET_o}$ following precipitation even if the estimated K_{cb} is small, due to surface evaporation from among sparse vegetation. In addition, K_{c} should be reduced via K_{s} when soil water is low.

The value for $K_{\mathrm{cb\ cover}}$ in Eq. 5b should represent the K_{cb} of the surface cover in the absence of the overstory cover, because Eq. 5b in essence estimates the change in K_{cb} occurring when an overstory tree or other crop replaces, via shading, some f_{c} fraction of the surface cover. The value for $K_{\mathrm{cb\ cover}}$ should reflect the density and vigor of the surface cover as occurring in sunlit areas.

The approach of Eq. 5a and 5b can be similarly applied to estimate a single K_{cm} coefficient for any period having less than full vegetative cover by accounting for the effect of evaporation from predominately exposed areas of soil among the vegetation, much the same as is done in the dual $K_{\mathrm{cb}} + K_{\mathrm{e}}$ approach:

$$K_{\mathrm{cm}} = K_{\mathrm{soil}} + K_{\mathrm{d}}\left(\max\left[K_{\mathrm{c\ full}} - K_{\mathrm{soil}}, \frac{K_{\mathrm{c\ full}} - K_{\mathrm{soil}}}{2}\right]\right) \tag{6}$$

where K_{soil} represents the average K_{c} from the non-vegetated (exposed) portion of the surface and reflects the impact of wetting frequency, soil type and relative ET rate (i.e., $\mathrm{ET_o}$) during the same period as K_{d} and $K_{\mathrm{c\ full}}$. The K_{cm} represents an average K_{c} value that considers the mean impact of evaporation from soil, as does $K_{\mathrm{c\ full}}$, representing K_{c} from a fully covered soil with some background evaporation. K_{cm} can be used to represent the midseason or other period as defined by K_{d}, K_{cm}, and $K_{\mathrm{c\ full}}$.

For large stand size (greater than about 500 m^2), $K_{\mathrm{cb\ full}}$ for use with $\mathrm{ET_o}$ can be approximated as a function of mean plant height and adjusted for climate following Allen et al. (1998):

$$(\text{for }\mathrm{ET_o})\ldots K_{\mathrm{cb\ full}} = F_{\mathrm{r}}\left(\min(1.0 + 0.1h, 1.20) + [0.04(u_2 - 2) - 0.004(\mathrm{RH_{min}} - 45)]\left(\frac{h}{3}\right)^{0.3}\right) \tag{7a}$$

For use with alfalfa reference $\mathrm{ET_r}$, $K_{\mathrm{cb\ full}}$ can be estimated as:

$$(\text{for }\mathrm{ET_r})\ldots K_{\mathrm{cb\ full}} = F_r(\min(0.8 + 0.1h, 1.0)) \tag{7b}$$

where h is mean maximum plant height in m, u_2 is the mean value for wind speed at 2 m height during the mid-season in m s^{-1}, $\mathrm{RH_{min}}$ is the mean value for minimum daily relative humidity during the mid-season in %, and F_{r} [0–1] is an adjustment factor relative to crop stomatal control, described below. The climatic correction is not required for $K_{\mathrm{cb\ full}}$ when used to derive the K_{cb} for $\mathrm{ET_r}$ because of the aerodynamic and canopy characteristics of the alfalfa reference crop. $K_{\mathrm{c\ full}}$ can generally be estimated as equivalent to $K_{\mathrm{cb\ full}}$ or equal to $K_{\mathrm{cb\ full}} + 0.05$ following Wright (1982) and Allen et al. (1998).

Equation 7a suggests that an upper bound for $K_{\mathrm{cb\ full}}$ is 1.20 for the grass reference basis, prior to adjustment for climate. The value for $K_{\mathrm{c\ full}}$ represents a general upper limit on $K_{\mathrm{cb\ mid}}$ for tall vegetation having full ground cover and LAI > 3 under full water supply. Equations 7a and 7b produce general approximations for the increase in $K_{\mathrm{cb\ full}}$ with plant height and climate.

Parameter F_{r} applies a downward adjustment ($F_{\mathrm{r}} \leq 1.0$) if the vegetation exhibits more stomatal control on transpiration than is typical of most annual agricultural crops. F_{r} may be <1 for some types of trees and natural vegetation. Allen et al. (1998) suggested the following calculation for reducer F_{r} for full cover vegetation, based on the FAO Penman–Monteith equation and assuming full cover conditions:

$$\mathrm{F_r} \approx \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma\left(1 + 0.34u_2\frac{r_1}{100}\right)} \tag{8}$$

where r_1 is mean leaf resistance for the vegetation in question [s m^{-1}], Δ is the slope of the saturation vapor pressure versus air temperature curve (kPa C^{-1}), and γ is the psychrometric constant (kPa C^{-1}). Factor F_{r} is multiplied against the estimate for $K_{\mathrm{cb\ full}}$ in Eq. 7a to reduce its value. The standard value for F_{r} is 1.0 because, for most annual agricultural crops, r_1 is often approximately 100 s m^{-1} (Körner et al. 1979; Allen et al. 1996). Values for r_1 for many agricultural and non-agricultural plants can be found in those publications and elsewhere, or r_1 can be estimated by inverting Eq. 8 after solving for F_{r} by inverting Eq. 7a or 7b using known $K_{\mathrm{cb\ full}}$. The application of Eq. 8 and value assigned to r_1 refers to full cover conditions for both the reference (100 s m^{-1}) and vegetation in question. Full cover conditions can generally be assumed to occur when the leaf area index (LAI) exceeds about 3. Where plant leaves and canopy are sparse so that LAI is less than about 3, even at full cover, the ratio $r_l/100$ in Eq. 8 can be replaced by $r_s/50$ (or $r_s/30$) where r_s is the estimated bulk canopy resistance for the full cover condition and 50 (or 30) is the value for r_s for the grass reference ET$_o$ (or alfalfa reference ET$_r$) when applied hourly (Allen et al. 2006). It should be recognized that r_l solved by inverting Eq. 7a and 8 is only an approximate estimate for r_l and contains artifacts of the $K_{cb\ full}$ measurement, weather data error, and the constructs of the two equations. Therefore, values for r_l determined by the inversion are only useful for reuse in Eq. 8.

Density coefficient

The density coefficient describes the increase in K_c with increase in amount of vegetation. The shape of the K_d curve is curvilinear with LAI or fraction of ground cover because of effects of microadvection of convective and radiative energy from exposed soil and height of vegetation. Where LAI can be measured or approximated, K_d can be approximated under normal conditions using an exponential function by Allen et al. (1998) used for estimating K_{cb} during midseason (Eq. 97 in FAO 56). The result is:

$$K_d = \left(1 - e^{[-0.7\mathrm{LAI}]}\right) \quad (9)$$

where LAI is defined as the area of leaves per area of ground surface averaged over a large area with units of m^2 m^{-2}. Only one side of 'green,' healthy leaves that are active in vapor transfer is counted. The relationship in Eq. 9 is similar to one used by Ritchie (1974).

While estimates of the fraction of ground surface covered by vegetation, f_c, are available, the K_d is estimated similar to Allen et al. (1998) as:

$$K_d = \min\left(1, M_L f_{c\ eff}, f_{c\ eff}^{\left(\frac{1}{1+h}\right)}\right) \quad (10)$$

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 [1.5–2.0], and h is the mean height of the vegetation in m. Estimation of $f_{c\ eff}$ was described in Allen et al. (1998). For canopies such as trees or randomly (nonrow) planted vegetation, $f_{c\ eff}$ can be estimated as:

$$f_{c\ eff} = \frac{f_c}{\sin(\beta)} \le 1 \quad (11)$$

where β is the mean angle of the sun above the horizon during the period of maximum ET (generally between 11.00 and 15.00) and f_c is the fraction of surface covered by vegetation as observed from directly overhead. f_c is often determined from visual inspection. However, digital image analysis or other measurement means can be employed. Generally, $f_{c\ eff}$ can be calculated at solar noon (12.00), so that β can be calculated as:

$$\beta = \arcsin[\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)] \quad (12)$$

where parameters φ and Δ are latitude ($-\pi/2 \le \varphi \le \pi/2$) and solar declination in radians. Allen et al. (1998) provided equations for estimating β for row crops as a function of row orientation. A schematic showing f_c, $f_{c\ eff}$ and β is shown in Fig. 4.

The M_L multiplier on $f_{c\ eff}$ in Eq. 10 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) and is expected to range from 1.5 to 2.0, depending on the canopy density and thickness. Parameter M_L is an attempt to simulate the physical limits imposed on water flux through the plant root, stem and leaf systems. The value for M_L can be modified to fit the specific vegetation.

Figure 5 shows values for K_d over a range of $f_{c\ eff}$ and a range of h for $M_L = 1.5$ and for $M_L = 2$ when $h = 5$ m, showing the effect of h and M_L on the estimate. Only K_d for h greater than about 1 m is impacted by varying the value for M_L from 1.5 to 2.0. The estimates by Eq. 10 closely reproduce individual functions previously suggested by

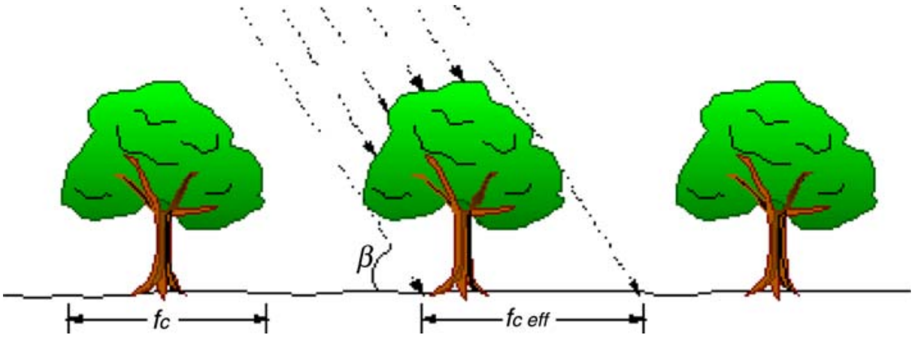

Fig. 4 Schematic showing extent of f_c, $f_{c\ eff}$ and β for tree vegetation where f_c is the fraction of surface covered by vegetation as measured from directly overhead

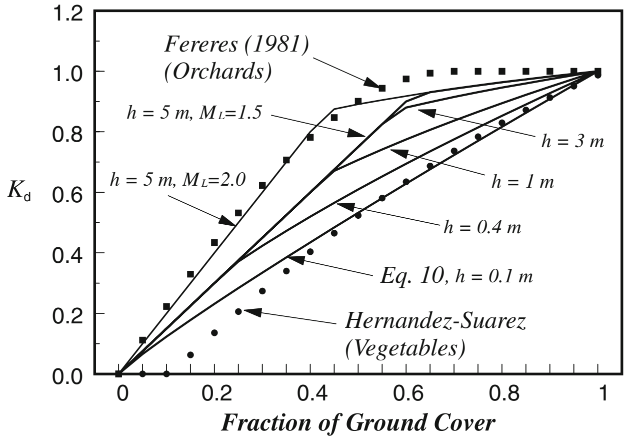

Fig. 5 Density coefficient, K_d, estimated from Eq. 10 with $M_L = 1.5$ over a range of fraction of ground cover and various plant heights, and compared with estimates by Fereres (1981) for orchards and Hernandez-Suarez (1988) for vegetables

Fereres (1981) for orchards (using $M_L = 2.0$) and Hernandez-Suarez (1988) for vegetables. The function by Fereres (1981) is the same as one recommended by Snyder and Eching (2005).

Equation 10 suggests that as h increases, total leaf area and resulting net radiation capture will increase, thereby increasing K_c. In addition, as h increases, more opportunity for microadvection and radiation of heat from soil to canopy occurs and turbulent exchange within the canopy increases for the same amount of ground coverage. Both of these increases increase the relative magnitude of K_{cb} or K_c. Values for K_{cb} or K_c can be scaled from estimates by Eq. 6 or 7a in proportion to the health and leaf condition of the vegetation at termination and the length of the late season period (i.e., whether leaves senesce slowly or are killed by frost). The f_c parameter and h are probably the simplest indices to estimate in the field.

Comparison of K_c from Eq. 6 based on K_d from Eq. 10 with reported data for vegetables

The close agreement with Fereres (1981), Snyder and Eching (2005), and Hernandez-Suarez (1988) suggests that the general form of Eq. 10 may be appropriate for a range of vegetation types and heights. The estimation of K_c from Eq. 6 using $K_{c\ full}$ from Eq. 7a and K_d from Eq. 10 was further compared with K_c data and regression equations reported by Grattan et al. (1998) and Hanson and May (2006). Grattan et al. (1998) reported the progression of K_c during plant development for seven vegetable crops in California as measured using Bowen ratio systems. They expressed K_c as a function of percent of ground cover, which is equivalent to f_c so that their data can be compared directly to that from Eqs. 6 and 10. Hanson and May (2006) additionally reported a polynomial equation for K_c versus f_c for tomatoes in California.

Equation 6 for K_c was applied rather than Eq. 5a for K_{cb} since some background soil evaporation appeared to be present for some of the crops. $K_{c\ full}$ was estimated as equivalent to $K_{cb\ full}$. In addition, f_c was used in Eq. 10 rather than $f_{c\ eff}$ because specific dates of vegetation development were not reported. Because the sun angle during late spring is high, differences between f_c and $f_{c\ eff}$ will be small. Because the crops of Grattan et al. (1998) were all annual or perennial vegetable crops, F_r in Eq. 7a was set to 1.0, implying an $r_l = 100\ \mathrm{s\ m^{-1}}$. The parameters used in Eqs. 6, 7a, and 10 for the vegetable crops are summarized in Table 1 as are root mean square error (RMSE) for the Eq. 6/10 combination and for the original regression equations of Grattan et al. (1998). Comparisons of Eq. 6/10, the regression equations by Grattan et al. and the Grattan et al. data are shown in Fig. 6 for the seven crops. Vegetation height was varied over time in Eq. 10 in proportion to the maximum estimated height times the ratio of specific f_c to f_c at full cover reported by Grattan et al. (1998), with the exception of cantaloupe, which was assumed to have nearly constant height due to its vine nature. Maximum values for h were taken from tables in Allen et al. (1998). A standard climate (wind speed = 2 m s^{-1} and daily minimum relative humidity = 45%) was assumed due to lack of reported data by Grattan et al. (1998). Due to the relatively short height of the crops, the adjustment for climate in Eq. 7a would be small.

The agreement between K_c from Eqs. 6, 7a, and 10 and the data of Grattan et al. (1998) was nearly as good as the fitted regression equations reported by Grattan et al. (1998), with the exception of artichokes where the Grattan regression fit the data better with its stronger curve (Fig. 6a). The accuracy of K_c from Eq. 6, 7a, and 10 appears to be within the measurement error of the reported K_c data. When $K_{soil} = 0.15$, Eq. 6 reverts to Eq. 5a that was developed for the basal K_{cb}. The larger values required for K_{soil} in Eq. 6 for beans and onion suggest that the soil surface was relatively moist for these two crops, as evidenced by values for measured K_c at low f_c. The publication of Hanson and May (2006) (tomato in Fig. 6) did not report the measurement data so that only their regression equation was compared against the product of Eqs. 6, 7a, and 10. The two estimates compared closely, suggesting that Eqs. 6, 7a, and 10, using readily estimated physical parameters, can be used to estimate K_c if visually assessed or other estimates of f_c are available.

The K_c from Eqs. 6, 7a, and 10 tends to have less curvature versus f_c compared to the curvilinear regression equations of Grattan et al. (1998). The K_c from Eq. 6, 7a, and 10 did express more curvilinearity for the tomato crop

Table 1 Parameters used in Eqs. 6, 7a, and 10 to estimate K_c for vegetable crops reported by Grattan et al. (1998)

Crop	Artichoke	Beans	Brocolli	Lettuce	Cantaloupe/honeydew	Onion	Strawberry	Tomato
K_{soil}	0.15	0.50	0.15	0.15	0.15	0.40	0.05	0.15
M_L	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
F_r	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Max h (m)	0.6	0.4	0.3	0.3	0.3	0.4	0.2	1.2
h versus time	In prop. to f_c	In prop. to f_c	In prop. to f_c	In prop. to f_c	Constant	In prop. to f_c	In prop. to f_c	In prop. to f_c
u_2 (m s^{-1})	2	2	2	2	2	2	2	2
RH_{min} (%)	45	45	45	45	45	45	45	45
No. obs.	11	27	34	39	35	14	10	–
$RMSE_{Grattan}$	0.09	0.09	0.13	0.16	0.09	0.10	0.05	–
$RMSE_{Eq.\ 6/10}$	0.15	0.10	0.14	0.17	0.10	0.11	0.10	–

of Hanson and May (2006) (Fig. 6h) due to the taller height of tomatoes compared to the other crops. The K_c from Eq. 6, 7a, and 10 approaches the $K_{cb\ full}$ estimated from Eq. 7a as f_c approaches 1.0.

Applications of Eqs. 5a–10 for K_c for orchards and grapes

Equations 5a–10 can be applied to estimate values for K_{cb} and K_c for various orchard crops and vines, including values representing K_{cb} and K_c at the beginning, mid- and end of a growing season, namely the $K_{cb\ ini}$, $K_{cb\ mid}$, and $K_{cb\ end}$ and $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ as used in the FAO-style linear K_c method of Doorenbos and Pruitt (1977) and Allen et al. (1998). Table 2 lists parameters used in Equations 5a–10 to produce $K_{cb\ ini}$, $K_{cb\ mid}$, and $K_{cb\ end}$ and $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ values for orchard crops as updated by Allen et al. (2007a, 2009) and listed in Table 3, where multiple entries are listed for a range of fraction of cover, f_c, summarized from the literature.

A single value is given in Table 2 for r_l for each orchard type to represent both beginning and midseason periods. These are the r_l values that explain, via Eqs. 7a and 8, the values for F_r that in turn explain, via $K_{cb\ full}$ and Eq. 5a or 6, values in Table 3 for $K_{cb\ ini}$ or $K_{c\ ini}$. They also explain values in Table 3 for $K_{cb\ mid}$ or $K_{c\ mid}$, depending on the Table 3 entry for f_c. In Table 3, ranges of values for f_c and corresponding values for K_c are given, based on reported literature, as footnoted, and as compared to later in Fig. 7. As noted in the next section, the K_{cb} values from cited measurements represented essentially bare surface conditions so that F_r was calculated by inverting Eq. 5a. The value for r_l at the end of the season explains the F_r value required to reduce the $K_{cb\ full}$ value estimated from Eqs. 7a and 7b to produce values for $K_{cb\ end}$ and $K_{c\ end}$ that agree with literature values, including those from FAO-56. Nearly all values for r_l exceed the $r_l = 100$ s m^{-1} associated with annual agricultural vegetation, indicating various degrees of stomatal control exhibited by orchard and vine crops under typical growing conditions. Olives, mango, citrus and palm had the highest values for r_l and therefore lowest values for F_r. Olives required F_r of only 0.55 to explain the measured K_c reported primarily from Spain, suggesting substantial stomatal control. Inversion of Eq. 8 to derive the equivalent r_l given F_r for olives suggested an r_l of about 1,000 s/m at 30°C air temperature and 700 s/m at 20°C at sea level. As noted following Eq. 8, it is recognized that r_l solved by inverting Eqs. 7a and 8 is only an approximate estimate for r_l and contains artifacts of the $K_{cb\ full}$ measurement, weather data error, and the constructs of the two equations. Therefore, values for r_l determined by the inversion are only useful for assessing relative differences among types of orchard crops and for reuse in Eq. 8. Therefore, r_l computed in this way must be evaluated with caution, and further improvements in the calculation procedures as well as input from other researchers is desired.

To utilize Table 2 to estimate K_{cb} for initial and late season periods for orchards or vine crops, the user enters the tabulated values for M_L, f_c, and h into Eq. 10 to estimate K_d, enters the tabulated value for r_l into Eq. 8 to estimate F_r, enters values for F_r and h into Eq. 7a or 7b for $K_{cb\ full}$, and then enters the values for $K_{cb\ full}$, K_d and $K_{c\ min}$ into Eq. 5a to determine $K_{cb\ ini}$ or $K_{cb\ end}$. Values for the midseason $K_{cb\ mid}$ are estimated similarly, although the value for fraction of cover, f_c, can vary widely, depending on the tree density, age and degree and type of pruning. The values given for f_c in Table 2 for the initial period reflect the amount of effective 'transpiring' surface at the time that $K_{c\ ini}$ occurs. For many orchard crops, the initial period may represent the time of flowering or late

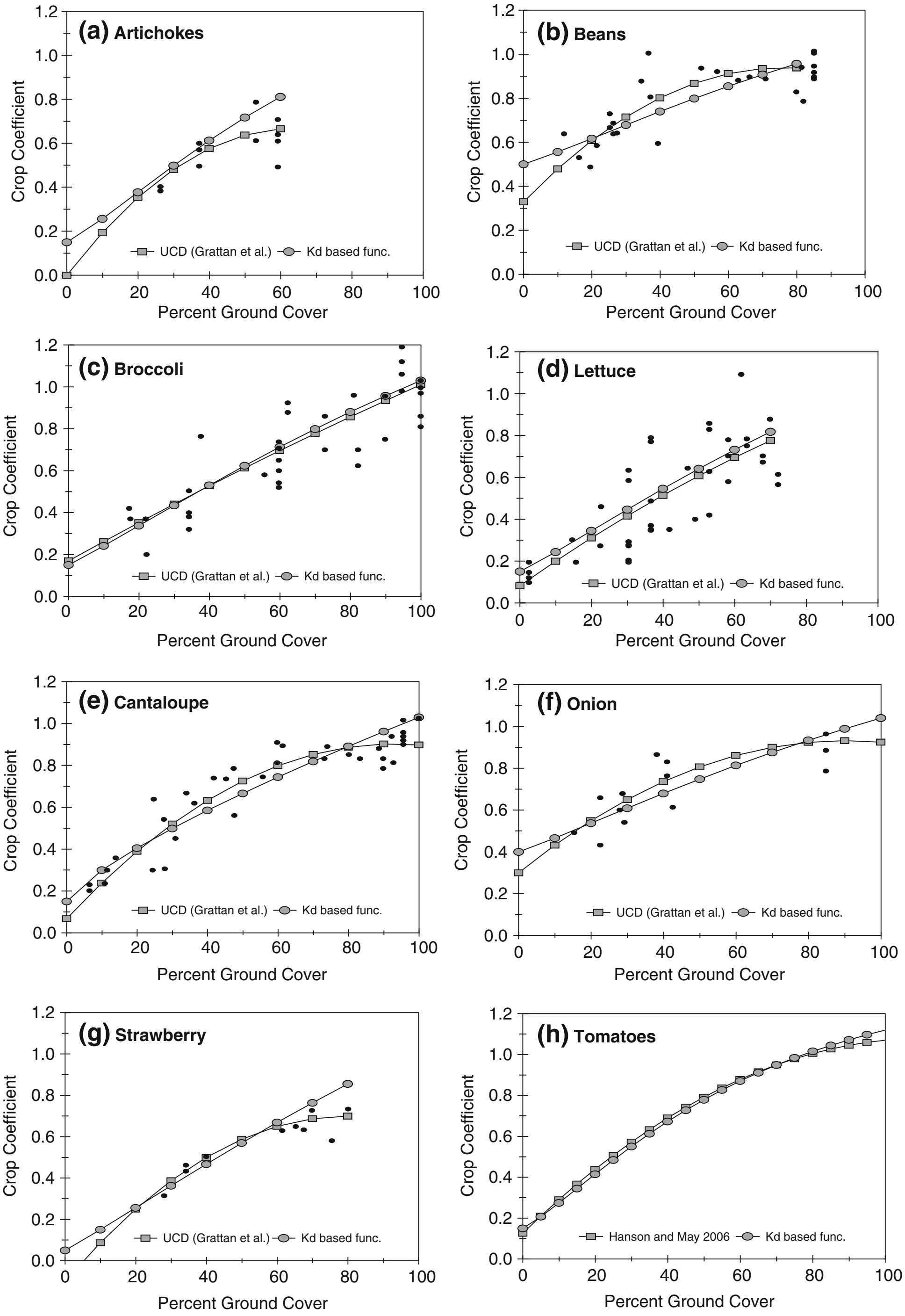

Fig. 6 K_c versus f_c for seven vegetable crops in California reported by Grattan et al. (1998) (**a**–**g**) and tomatoes in California by Hanson and May (2006) (**h**), showing data and regression equations by Grattan et al. and Hanson and May (2006) with K_c estimated using Eqs. 6, 7a, and 10. The *small black symbols* represent measured data

dormancy prior to leaf development. That period, and the period of development prior to the midseason period, may be relatively short.

If a ground-cover is present in the orchard system, then Eq. 5b is applied to determine K_{cb}, where the $K_{cb\ cover}$ represents the basal K_{cb} for the ground cover in the absence of the orchard. The value for $K_{cb\ cover}$ will range widely depending on the density, type and management of the ground cover.

In the case of estimating values for the single (mean) K_c, the K_{soil} parameter in Eq. 6 can be estimated using the Figures 29 and 30 of FAO-56 (Allen et al. 1998), Eq. 18 of Allen et al. 2005b, or by averaging a daily estimate of soil evaporation via a daily soil water balance, such as the K_e computation of FAO-56 (Allen et al. 1998, 2005a).

Table 3 contains entries for grass ET$_o$-based $K_{c\ ini}$, $K_{c\ mid}$, $K_{c\ end}$, $K_{cb\ ini}$, $K_{cb\ mid}$, and $K_{cb\ end}$ for a number of

Table 2 Parameters for use in Eqs. 6, 7a, and 10 to produce, in general, the values for $K_{c\ ini}$, $K_{c\ mid}$, $K_{c\ end}$, $K_{cb\ ini}$, $K_{cb\ mid}$, and $K_{cb\ end}$ listed in Table 3, assuming a standard climate of $RH_{min} = 45\%$ and $u_2 = 2$ m s^{-1}

	M_L	h (m)	f_c at start of initial period	Condition at start of initial period	Apparent, effective r_l for initial and midseason periods to explain F_r [a] equiv. to LAI = 3	F_r for initial and midseason periods (to estimate $K_{cb\ ini}$, $K_{cb\ mid}$, $K_{c\ ini}$, and $K_{c\ mid}$)	f_c at end of season	Apparent, effective r_l at end of season to explain F_r [a] equiv. to LAI = 3	F_r at end of season (to estimate $K_{cb\ end}$ and $K_{c\ end}$)
Almonds	1.5	4	0.05	Bare ground	300	0.81	0.55	650	0.59
Apples, cherries, pears									
Killing frost	2.0	3	0.10	Flowering	140	0.95	0.40	450	0.69
No frosts	2.0	3	0.20	Flowering	140	0.95	0.40	370	0.75
Apricots, peaches, stone fruit									
Killing frost	1.5	3	0.15	Flowering	100	1.00	0.45	430	0.71
Avocado									
No ground cover	2.0	3	0.20	Flowering	300	0.81	0.40	400	0.73
Citrus									
No ground cover	1.5	2	0.25	Old leaves	420	0.71	0.20	150	0.94
Ground cover	1.5	2.5	0.45	Old leaves	420	0.71	0.40	275	0.82
Mango									
No ground cover	1.5	5	0.00		500	0.67	0.50	725	0.56
Olives									
No ground cover	1.5	4	0.55	Old leaves	950	0.48	0.70	1,000	0.46
Pistachios									
No ground cover	1.5	3	0.05	Bare ground	300	0.81	0.70	700	0.57
Walnut									
No ground cover	1.5	5	0.20	Flowering	180	0.90	0.70	800	0.52
Palms									
No ground cover	1.5	8	0.58	Old leaves	414	0.71	0.70	362	0.75
Grapes									
Table or raisin	1.5	2	0.00	Bare ground	139	0.95	0.40	851	0.51
Grapes									
Wine	1.5	1.5	0.00	Bare ground	523	0.65	0.50	1,149	0.43

Parameter f_c during midseason, shown in Table 3, is not listed here, as it has multiple entries in Table 3. $K_{cb\ min}$ is assumed to be 0.15 in all cases

[a] These values for r_l are normalized via inversion of Eq. 8 for an LAI ~3, so that the F_r from Eq. 8 can be used in Eq. 7a to estimate $K_{cb\ full}$

Table 3 Values for $K_{c\ ini}$, $K_{c\ mid}$, $K_{c\ end}$, $K_{cb\ ini}$, $K_{cb\ mid}$, and $K_{cb\ end}$ for a standard climate of $RH_{min} = 45\%$ and $u_2 = 2$ m s^{-1} as expanded from FAO-56 for a range of values for f_c during midseason and using parameter values in Table 2 in Eqs. 5a–10

Crop	$K_{c\ ini}$[a]	$K_{c\ mid}$	$K_{c\ end}$	$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$
Fruit trees						
Almonds						
No ground cover						
High density ($f_{c\ eff} = 0.7$)	0.40	1.00	0.70[b]	0.20	0.95	0.65[b]
Med. density ($f_{c\ eff} = 0.5$)[c]	0.40	0.85	0.60[b]	0.20	0.80	0.55[b]
Low dens./young ($f_{c\ eff} = 0.25$)	0.35	0.50	0.40[b]	0.15	0.45	0.35[b]
Active ground cover						
High density ($f_{c\ eff} = 0.7$)[j]	0.85	1.05	0.85[b]	0.75	1.00	0.80[b]
Med. density ($f_{c\ eff} = 0.5$)	0.85	1.00	0.85[b]	0.75	0.95	0.80[b]
Low dens./young ($f_{c\ eff} = 0.25$)	0.85	0.95	0.85[b]	0.75	0.90	0.80[b]
Apples, cherries, pears						
No ground cover						
High density ($f_{c\ eff} = 0.7$)	0.50	1.15	0.80[b]	0.30	1.10	0.75[b]
Med. density ($f_{c\ eff} = 0.5$)[c]	0.50	1.05	0.75[b]	0.30	1.00[d]	0.70[b]
Low dens./young ($f_{c\ eff} = 0.25$)	0.40	0.70	0.55[b]	0.25	0.65	0.50[b]
Active ground cover						
Killing frost, h. dens. ($f_{c\ eff} = 0.7$)[j]	0.50	1.20	0.85[b]	0.40	1.15	0.80[b]
Killing frost, m. dens. ($f_{c\ eff} = 0.5$)[c]	0.50	1.15	0.85[b]	0.40	1.10	0.80[b]
Killing frost, l. dens. ($f_{c\ eff} = 0.25$)	0.50	1.05	0.85[b]	0.40	1.00	0.80[b]
No frosts, h. dens. ($f_{c\ eff} = 0.7$)	0.85	1.20	0.85[b]	0.75	1.15	0.80[b]
No frosts, m. dens. ($f_{c\ eff} = 0.5$)[c]	0.85	1.15	0.85[b]	0.75	1.10	0.80[b]
No frosts, l. dens. ($f_{c\ eff} = 0.25$)	0.85	1.05	0.85[b]	0.75	1.00	0.80[b]
Apricots, peaches, stone fruit[e]						
No ground cover						
Super density ($f_{c\ eff} = 0.9$)[f]	0.50	1.20	0.85[b]	0.30	1.15	0.80[b]
High density ($f_{c\ eff} = 0.7$)[g]	0.50	1.15	0.80[b]	0.30	1.10	0.75[b]
Med. density ($f_{c\ eff} = 0.5$)[c]	0.45	1.0	0.70[b]	0.25	0.95	0.65[b]
Low dens./young ($f_{c\ eff} = 0.25$)[h]	0.40	0.60	0.45[b]	0.20	0.55	0.40[b]
Active ground cover						
Killing frost, s. dens. ($f_{c\ eff} = 0.9$)[j]	0.50	1.25	0.85[b]	0.40	1.20	0.80[b]
Killing frost, h. dens. ($f_{c\ eff} = 0.7$)[c]	0.50	1.20	0.85[b]	0.40	1.15	0.80[b]
Killing frost, m. dens. ($f_{c\ eff} = 0.5$)	0.50	1.15	0.85[b]	0.40	1.10	0.80[b]
Killing frost, l. dens. ($f_{c\ eff} = 0.25$)	0.50	1.00	0.85[b]	0.40	0.95	0.80[b]
No frosts, s. dens. ($f_{c\ eff} = 0.9$)	0.80	1.25	0.85[b]	0.70	1.20	0.80[b]
No frosts, h. dens. ($f_{c\ eff} = 0.7$)[c]	0.80	1.20	0.85[b]	0.70	1.15	0.80[b]
No frosts, m. dens. ($f_{c\ eff} = 0.5$)	0.80	1.15	0.85[b]	0.70	1.10	0.80[b]
No frosts, l. dens. ($f_{c\ eff} = 0.25$)	0.80	1.00	0.85[b]	0.70	0.95	0.80[b]
Avocado						
No ground cover						
High density ($f_{c\ eff} = 0.7$)	0.50	1.00	0.90	0.30	0.95	0.85
Med. density ($f_{c\ eff} = 0.5$)[c]	0.50	0.90	0.80	0.30	0.85	0.80
Low dens./young ($f_{c\ eff} = 0.25$)	0.40	0.65	0.60	0.25	0.60	0.50
Active ground cover						
High density ($f_{c\ eff} = 0.7$)[j]	0.85	1.05	0.95	0.75	1.00	0.90
Med. density ($f_{c\ eff} = 0.5$)	0.85	1.00	0.95	0.75	0.95	0.90
Low dens./young ($f_{c\ eff} = 0.25$)	0.85	0.95	0.90	0.75	0.90	0.85

Table 3 continued

Crop	$K_{c\ ini}^{a}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$
Citrus						
No ground cover						
High density ($f_{c\ eff} = 0.7$)[i]	0.95	0.90	0.90	0.85	0.85	0.85
Med. density ($f_{c\ eff} = 0.5$)	0.80	0.75	0.75	0.70	0.70	0.70
Low dens./young ($f_{c\ eff} = 0.25$)	0.55	0.50	0.50	0.45	0.45	0.45
Active ground cover						
High density ($f_{c\ eff} = 0.7$)[j,k]	1.00	0.95	0.95	0.90	0.90	0.90
Med. density ($f_{c\ eff} = 0.5$)	0.95	0.95	0.95	0.85	0.90	0.90
Low dens./young ($f_{c\ eff} = 0.25$)	0.90	0.90	0.90	0.80	0.85	0.85
Mango						
No ground cover						
High density ($f_{c\ eff} = 0.7$)[l]	0.35	0.90	0.75	0.25	0.85	0.70
Med. density ($f_{c\ eff} = 0.5$)	0.35	0.75	0.60	0.25	0.70	0.55
Low dens./young ($f_{c\ eff} = 0.25$)	0.30	0.45	0.40	0.20	0.40	0.35
Olives						
No ground cover						
High density ($f_{c\ eff} = 0.7$)[c,m]	0.65	0.70	0.60	0.55	0.65	0.55
Med. density ($f_{c\ eff} = 0.5$)[n]	0.60	0.60	0.55	0.50	0.55	0.50
Low dens./young ($f_{c\ eff} = 0.25$)[o]	0.40	0.40	0.35	0.30	0.35	0.30
V. low dens./young ($f_{c\ eff} = 0.05$)[o]	0.30	0.25	0.25	0.20	0.20	0.20
Active ground cover						
High density ($f_{c\ eff} = 0.7$)[j]	0.80	0.75	0.75	0.70	0.70	0.70
Med. density ($f_{c\ eff} = 0.5$)	0.80	0.75	0.75	0.70	0.70	0.70
Low dens./young ($f_{c\ eff} = 0.25$)	0.80	0.75	0.75	0.70	0.70	0.70
V. low dens./young ($f_{c\ eff} = 0.05$)	0.80	0.75	0.75	0.70	0.70	0.70
Pistachios						
No ground cover						
High density ($f_{c\ eff} = 0.7$)	0.40	1.00	0.70	0.30	0.95	0.65
Med. density ($f_{c\ eff} = 0.5$)	0.35	0.85	0.60	0.25	0.80	0.55
Low dens./young ($f_{c\ eff} = 0.25$)	0.30	0.50	0.40	0.20	0.45	0.35
Active ground cover						
High density ($f_{c\ eff} = 0.7$)	0.80	1.00	0.75	0.70	0.95	0.70
Med. density ($f_{c\ eff} = 0.5$)	0.80	1.00	0.75	0.70	0.95	0.70
Low dens./young ($f_{c\ eff} = 0.25$)	0.80	0.85	0.75	0.70	0.80	0.70
Walnut Orchard						
No ground cover						
High density ($f_{c\ eff} = 0.7$)	0.50	1.10	0.65[b]	0.40	1.05	0.60[b]
Med. density ($f_{c\ eff} = 0.5$)	0.45	0.90	0.60[b]	0.35	0.85	0.55[b]
Low dens./young ($f_{c\ eff} = 0.25$)	0.35	0.55	0.40[b]	0.25	0.50	0.35[b]
Active ground cover						
High density ($f_{c\ eff} = 0.7$)[j]	0.85	1.15	0.85[b]	0.75	1.10	0.80[b]
Med. density ($f_{c\ eff} = 0.5$)	0.85	1.10	0.85[b]	0.75	1.05	0.80[b]
Low dens./young ($f_{c\ eff} = 0.25$)	0.85	0.95	0.85[b]	0.75	0.90	0.80[b]
Palms (including date palms)						
No ground cover						
High density ($f_{c\ eff} = 0.7$)[c]	0.90	0.95	0.95	0.80	0.85	0.85
Med. density ($f_{c\ eff} = 0.5$)	0.80	0.80	0.80	0.70	0.70	0.70
Low dens./young ($f_{c\ eff} = 0.25$)	0.50	0.55	0.55	0.40	0.45	0.45

Table 3 continued

Crop	$K_{c\ ini}^{a}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$
V. low dens./young ($f_{c\ eff} = 0.1$)	0.35	0.35	0.35	0.25	0.25	0.25
Active ground cover						
High density ($f_{c\ eff} = 0.7$)	0.95	0.95	0.95	0.85	0.90	0.90
Med. density ($f_{c\ eff} = 0.5$)	0.90	0.90	0.90	0.80	0.85	0.85
Low dens./young ($f_{c\ eff} = 0.25$)	0.85	0.85	0.85	0.75	0.80	0.80
V. low dens./young ($f_{c\ eff} = 0.1$)	0.80	0.80	0.80	0.70	0.75	0.75
Grapes: table or raisin						
No ground cover						
High density ($f_{c\ eff} = 0.7$)[f]	0.30	1.10	0.85[b]	0.20	1.05	0.80[b]
Med. density ($f_{c\ eff} = 0.5$)[c]	0.30	0.95	0.75[b]	0.20	0.90	0.70[b]
Low/young ($f_{c\ eff} = 0.25$)	0.30	0.60	0.50[b]	0.20	0.55	0.45[b]
Grapes: wine						
No ground cover						
High density ($f_{c\ eff} = 0.7$)	0.30	0.75[p]	0.60[bp]	0.20	0.70[p]	0.55[bp]
Med. density ($f_{c\ eff} = 0.5$)[c]	0.30	0.70[p]	0.55[bp]	0.20	0.65[p]	0.50[bp]
Low/young ($f_{c\ eff} = 0.25$)	0.30	0.45[p]	0.40[bp]	0.25	0.40[p]	0.30[bp]

Many of the values for f_c and $K_{c\ mid}$ are compared to values reported in specific literature (after Allen et al. 2007a)

[a] These are general values for $K_{c\ ini}$ under typical irrigation management and soil wetting. For frequent wettings such as with high frequency sprinkle irrigation or daily rainfall, these values may increase substantially and may approach 1.0–1.2. $K_{c\ ini}$ is a function of wetting interval and potential evaporation rate during the initial and development periods and is more accurately estimated using Figures 29 and 30 of FAO-56, an equation from Allen et al. (2005b), or using the dual $K_{cb\ ini} + K_e$ calculation

[b] These $K_{c\ end}$ values represent K_c prior to leaf drop. After leaf drop, $K_{c\ end} \approx 0.20$ for bare, dry soil or dead ground cover and $K_{c\ end} \approx 0.50$–0.80 for actively growing ground cover

[c] The values in this row are similar to the entry in FAO-56 (Allen et al. 1998)

[d] For pears having $f_{c\ eff} = 0.5$, Girona et al. (2003) measured $K_{cb\ mid} = 0.85$, which is estimated using Eq.5a and 10 with $K_{cb\ full} = 1.1$ and $M_L = 1.5$

[e] Stone fruit category applies to peaches, apricots, pears, plums and pecans

[f] The values in this row are similar to those by Johnson et al. (2005)

[g] The values in this row are derived from Girona et al. (2005)

[h] The values in this row are similar to those by Paço et al. (2006)

[i] The values for citrus are about 20% higher than those reported in FAO-56

[j] For non-active or only moderately active ground cover (active indicates green and growing ground cover with LAI > about 2), K_c should be weighted between K_c for no ground cover and K_c for active ground cover, with the weighting based on the "greenness" and approximate leaf area of the ground cover

[k] The values in this row are similar to those by Rogers et al. (1983) for citrus in Florida having Bahia grass cover

[l] The values in this row are derived from de Azevedo et al. (2003)

[m] Pastor and Orgaz (1994) found monthly K_c for olive orchards having $f_c \sim 0.6$ similar to the values shown, except that $K_{c\ mid} = 0.45$, and using K_c during the winter ("off season") in December–February = 0.50

[n] The values in this row are similar to those by Villalobos et al. (2000) when $f_{c\ eff}$ of $\sim$0.3–0.4 are applied

[o] The values in this row are derived from Testi et al. (2004)

[p] These $K_{c\ mid}$ and $K_{c\ end}$ values include an implicit K_s (stress) factor of about 0.7 (see Eqs. 1 and 2), which is common for wine production. In practice, a K_s model and estimate should be applied where K_s can range from 0.5 to 1.0. Under no stress, the $K_{c\ mid}$ and $K_{c\ end}$ for wine grapes may equal that for table grapes, depending on plant density, age, and pruning structure

orchard crops and grapes as expanded from the FAO-56 tables by Allen et al. (2007a, b). The values for K_c reflect a standard climate having $\mathrm{RH}_{\min} = 45\%$ and $u_2 = 2\ \mathrm{m\ s^{-1}}$. The K_c values cover a range of values for f_c during midseason that contain entries that follow f_c and K_c taken from literature, and where the K_c values can be largely produced using parameter values listed in Table 4 using Eqs. 5a–10.

Values for potential $K_{cb\ full}$ were estimated from Eq. 7a using h and represent $K_{cb\ full}$ at maximum f_c. In nearly all cases, the potential $K_{cb\ full}$ was 1.2 for the orchard crops for the $\mathrm{ET_o}$ basis.

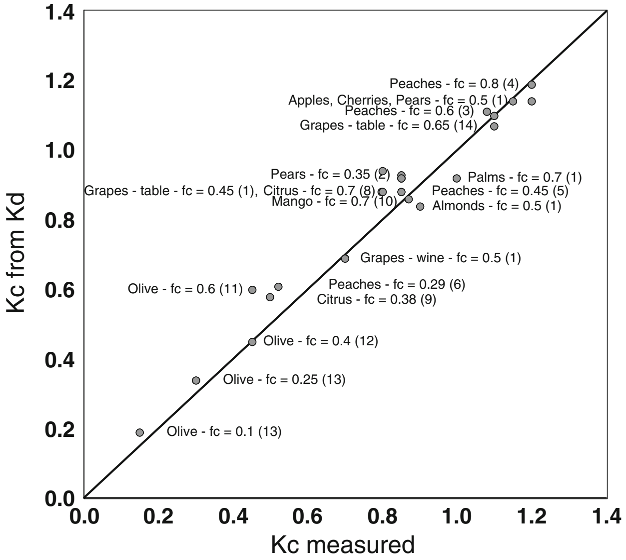

Fig. 7 $K_{cb\ mid}$ or $K_{c\ mid}$ estimated using Eqs. 5a-10 and parameters in Tables 2 and 5 versus $K_{cb\ mid}$ or $K_{c\ mid}$ as reported for various orchard and grape measurements in the literature for midseason growing conditions

Comparison of K_c from Eq. 5a or 6 based on K_d from Eq. 10 with reported data for orchards and grapes

Estimates for $K_{cb\ mid}$ or $K_{c\ mid}$ based on Eqs. 5a–10. and parameters in Tables 2, 4, and 5 are plotted in Fig. 7 against values for $K_{cb\ mid}$ or $K_{c\ mid}$ as reported for various orchard and grape measurements in the literature as cited below. The estimates for $K_{cb\ mid}$ or $K_{c\ mid}$ utilized f_c and h similar to those reported for the studies. The reported studies were all for essentially bare soil surface, so that Eq. 5a was used rather than Eq. 5b. In nearly all cases, the estimated K_c agreed relatively closely with measured, indicating that the series of equations and parameters from Table 2 may be useful to estimate K_c for other conditions. The values for r_l listed in Table 2 and that were used in Eq. 8 to estimate F_r that was in turn used in Eq. 7a to estimate $K_{cb\ full}$, were specifically derived for each crop, based on reported K_{cb}, so that the precautions and limitations previously noted should apply.

The literature sources cited in Fig. 7 are (1) Allen et al. (1998), (2) Girona et al. (2003), (3) Girona et al. (2005), (4) Johnson et al. (2005) (for microspray irrigation and dense, wet vegetation), (5) Ayars et al. (2003), (6) Paço et al. (2006), (7) FAO56 (Allen et al. 1998), (8) Consoli et al. (2005), (9) Alba et al. (2006), (10) de Azevedo et al. (2003), (11) Pastor and Orgaz (1994), (12) Villalobos et al. (2000) ($f_c = 0.4$), (13) Testi et al. (2004), and (14) Allen et al. (1998).

The relationship between K_c and f_c established by Eqs. 5a–10 is not singular but varies with crop height, relative stomatal resistance (r_l), and in some cases, the background soil evaporation. The nonsingularity is demonstrated in Fig. 8 where measured K_c is plotted as a function of reported f_c. The relatively large degree of scatter in the figure suggests that both height and stomatal control impact the value for K_c and should be considered during estimation.

Applications of Eqs. 5a and 10 for K_c to natural vegetation

Ringersma and Sikking (2001) applied equations similar to Eqs. 5a, 7a, and 9 to estimate ET from Sahelian vegetation barriers. They found Eq. 7a to overestimate $K_{cb\ full}$, even with adjustment using F_r from Eq. 8, but found Eq. 9 to produce representative estimates when combined with Eq. 5a. Ringersma and Sikking suggested distinction between C3 and C4 photosynthetic behavior for LAI and f_c based estimation, since C4 vegetation can have limited stomatal control. Descheemaeker et al. (2007) applied equations similar to Eqs. 5a, 6, 7a, and 9 to savannah vegetation in Ethiopia, and found good agreement between estimated ET and ET determined gravimetrically. Vegetation types ranged from sparse, grazed grasses to full forest canopy.

Summary and Conclusions

The FAO-56 procedure for estimating the crop coefficient K_c as a function of fraction of ground cover and crop height has been formalized in this study using a density coefficient K_d. K_d is multiplied by a K_c representing full cover conditions, $K_{cb\ full}$, to produce K_{cb} representing the actual conditions of ground coverage. $K_{cb\ full}$ is estimated primarily as a function of crop height. $K_{cb\ full}$ can be adjusted for tree crops by multiplying by a reduction factor estimated using a mean leaf stomatal resistance term. The estimate for basal crop coefficient, K_{cb}, is further modified for tree crops if some type of ground-cover exists understory or between trees. The single (mean) crop coefficient is adjusted using a K_{soil} coefficient that represents background evaporation from wet soil.

The K_c estimation procedure was applied to the development periods for seven vegetable crops grown in California by Grattan et al. (1998). The estimates were compared to measured K_c as well as to polynomial equations fitted by Grattan. The estimation accuracy of the generalized method was nearly as good as the regressions fit by Grattan. The K_c estimation procedure was further applied to estimate K_c during midseason periods of horticultural crops (trees and vines) reported in the literature. Values for mean leaf stomatal resistance and the F_r reduction factor were derived that explain the literature K_c values.

Table 4 Parameters that can be used in Eq. 5a or 5b to estimate $K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$ in Table 3 using $f_{c\ eff}$ in Table 3

Category	Equiv. $K_{cb\ full}$ Initial	$K_{cb\ full}$ Mid	Equiv. $K_{cb\ full}$ End	$K_{c\ min}$	$K_{cb\ cover}$ Initial[a]	$K_{cb\ cover}$ Mid, End[a]	Added[b] to $K_{cb\ ini}$ for $K_{c\ ini}$	Added[b] to $K_{cb\ mid}$ for $K_{c\ mid}$	Added[b] to $K_{cb\ end}$ for $K_{c\ end}$
Almonds									
No ground cover	0.20	1.00	0.70[c]	0.15	–	–	0.20	0.05	0.05
Ground cover	0.20	1.00	0.70[c]	0.15	0.75	0.80	0.10	0.05	0.05
Apples, cherries, pears									
Killing frost	0.30	1.15	0.80[c]	0.15	0.40	0.80	0.20	0.05	0.05
No killing frost	0.30	1.15	0.80[c]	0.15	0.75	0.80	0.10	0.05	0.05
Apricots, peaches, pears, plums, pecans									
Killing frost	0.30	1.20	0.80[c]	0.15	0.40	0.80	0.20	0.05	0.05
No killing frost	0.30	1.20	0.80[c]	0.15	0.70	0.80	0.10	0.05	0.05
Avocado									
No ground cover	0.30	1.00	0.90	0.15	–	–	0.20	0.05	0.05
Ground cover	0.30	1.00	0.90	0.15	0.75	0.80	0.10	0.05	0.05
Citrus	0.90	0.90	0.90	0.15	0.75	0.80	0.10	0.05	0.05
Mango									
No ground cover	0.25	0.85	0.70	0.15			0.10	0.05	0.05
Olives	0.60	0.70	0.60	0.15	0.70	0.70	0.10	0.05	0.05
Pistachios	0.30	1.00	0.70	0.15	0.70	0.70	0.10	0.05	0.05
Walnut	0.40	1.10	0.65[c]	0.15	0.75	0.80	0.10	0.05	0.05
Palms									
No ground cover	0.85	0.90	0.90	0.15			0.10	0.10	0.10
Ground cover	0.85	0.90	0.90	0.15	0.70	0.70	0.10	0.05	0.05
Grapes									
Table or raison	0.20	1.15	0.90[c]	0.15			0.10	0.05	0.05
Wine	0.20	0.80	0.60	0.15			0.10	0.05	0.05

[a] The values for $K_{cb\ cover}$ represent the K_c of the surface cover in full sunlight (i.e., as occurring in the absence of the overstory of the tree)

[b] The last three columns are values that were added to K_{cb} values estimated for the initial, midseason and late season periods to produce mean (single) values for K_c that include effects of evaporation from soil

[c] These $K_{c\ full}$ values for the end of season represent K_c for full cover conditions prior to leaf drop. After leaf drop, $K_{c\ end} \approx 0.20$ for bare, dry soil or dead ground cover and $K_{c\ end} \approx 0.50$–0.80 for actively growing ground cover

Table 5 Mean plant height, *h*, used in Eq. 7a and 10 for estimating $K_{cb\ ini}$, $K_{cb\ mid}$, and $K_{cb\ end}$ in Table 3

Category	$f_{c\ eff}$ = 0.05–0.1	$f_{c\ eff} = 0.25$	$f_{c\ eff} = 0.5$	$f_{c\ eff} = 0.7$	$f_{c\ eff} = 0.9$
Almonds		3	4	5	
Apples, Cherries, Pears		3	3	4	
Apricots, Peaches, Stone Fruit		2.5	3	3	3
Avocado		3	3	4	
Citrus		2	2.5	3	
Mango		4	4	5	
Olives	2	3	4	4	
Pistachios		2	2.5	3	
Walnut		4	4	5	
Palms	8	8	8	8	
Grapes					
Table or raison		2	2	2	
Wine		1.5	1.5	1.5	

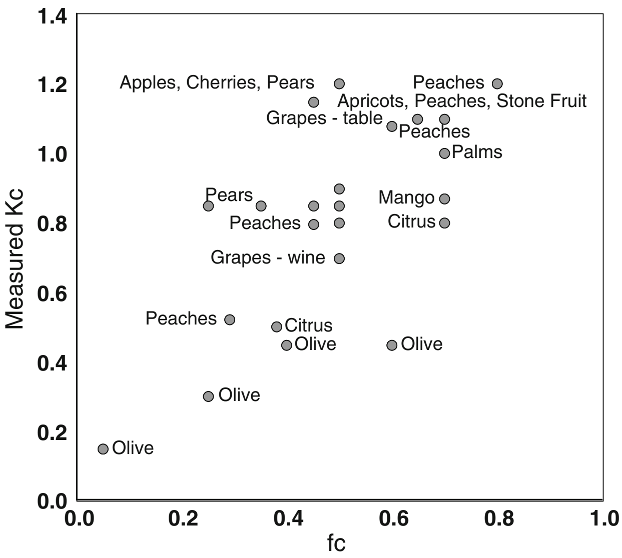

Fig. 8 Measured K_c reported in the literature plotted as a function of reported f_c for midseason conditions

The generalized method does not replace measurement of K_c for developing crop coefficient curves. However, it does provide a consistent means to assess measured values for reasonableness as well as providing a means to estimate change in values for K_c with change in fraction of ground covered by vegetation. This is important when estimating K_c for orchard crops which can vary widely in plant spacing, tree pruning, and age.

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