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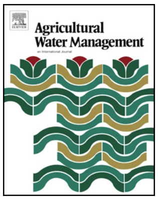

# Crop evapotranspiration estimation with FAO56: Past and future

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ABSTRACT

The FAO Irrigation and Drainage Paper No 56 on Crop Evapotranspiration has been in publication for more than 15 years. The paper advanced the accuracy and consistency of operational computation of evapotranspiration (ET) for agricultural and other land use types. The paper included updated definition and procedures for computing reference ET, an update on estimating crop coefficients ($K_c$), the adoption of the dual $K_c$ for separate estimation of crop transpiration and soil evaporation, and an upgraded estimation of crop ET under water and salt stress and other non-standard conditions. These advances are retrospectively reviewed in this paper. The advances in computing reference ET were primarily through the adoption of specific and consistent characteristics for the grass reference crop using the Penman–Monteith equation parameterized to represent a living reference surface. That standardization made the $K_c$ more visual and understandable as a factor that relates the ET characteristics of a specific crop to the defined reference crop. Methodologies were introduced to estimate reference ET under conditions of limited weather data while retaining the use of the PM equation. Advances in adopted $K_c$ research included techniques to estimate $K_c$ based on the architecture of crops, notably height and fraction of ground cover. Other advances included consistent and straight-forward techniques for applying the dual $K_c$ method via soil and evaporation process modeling on a daily timestep. New techniques were introduced for using yield response and salinity threshold values to estimate reductions in ET caused by elevated soil salinity. In addition, recommendations were given for adjusting ET for impacts of surface mulching, intercropping, and sparse vegetation. The successful adoption of the FAO–PM reference ET and $K_c$ approaches owes primarily to the simplicity, yet relatively high level of robustness of the procedures, and to transferability and repeatability of the $K_c$ method. Future development needs are discussed.

## 1. Introduction

The FAO Irrigation and Drainage Paper No 56 “Crop Evapotranspiration” was introduced in 1998 by the Food and Agriculture Organization of the United Nations, to revise guidelines for computing crop water requirements (Allen et al., 1998). Since its publication FAO56 has become one of FAO’s best selling publications and, with more than 11,500 citations in research articles (Google Scholar, July 2014), has become one of the most quoted publications in the field of crop water relationships. FAO56 has been translated into Russian and Spanish, with translations to Chinese and French pending after some time.[1] Fifteen years after its publication, we have an opportunity to look back on the merits of FAO56 and assess how relevant the guidelines still are, in view of recent advances in research, data availability, and modeling capabilities, and how the methodology should respond to new challenges and demands in the field of crop water relationships.

The FAO56 guidelines were a follow-on to the historic FAO paper No 24 by Doorenbos and Pruitt (1977), which introduced, internationally, in 1977, the two-step crop coefficient–reference ET ($K_c$–$ET_{ref}$) procedure to estimate crop water requirements in a practical way. In this approach, reference evapotranspiration ($ET_{ref}$) represents the primary weather induced effects on water consumption, and the crop coefficient ($K_c$) scales the reference ET to

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[1] The Chinese and French translations of FAO56 were completed in about 2005 through voluntary efforts outside FAO. FAO has not yet published these translations.

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account for crop-specific influences on ET and their variation during the crop growing season. Standardized values for $K_c$ for each of four typical crop stages were provided for a large number of crop types. The $K_c$–$ET_{ref}$ approach is intentionally simple and accessible to a wide range of users and uses. Its structure is intended to both guide and 'protect' against large over- and under-estimation of ET that had previously plagued many applications. Four methods were presented in FAO24 to estimate $ET_{ref}$, based on perceived data availability, including a modified Penman combination equation, a modified Blaney Criddle method, a Solar Radiation-based method and a Pan Evaporation-based method. Although the multiple $ET_{ref}$ methods were calibrated toward a common $ET_{ref}$ basis of clipped, cool season grass and provided freedom to users for matching method to data, many users expressed frustration with $ET_{ref}$ selection and with the common differences in results among methods. As a consequence, FAO56 reduced the reference ET process to a single method, the Penman–Monteith (Monteith, 1965; Smith et al., 1991).

The contributions of FAO56 included a more in-depth analysis and decomposition of the two-stage $K_c$–$ET_{ref}$ approach for estimating crop water use and the further expansion of $K_c$ to estimate crop ET under various crop growth and management conditions, accounting for the influences of (a) crop growth stage, amount of vegetation, and cultivar type; (b) the planting date, crop season length, and termination; (c) plant and row spacings, plant density, crop height and canopy architecture; (d) the wetting frequency and its contribution to total ET; (e) soil water availability and associated water stress; (f) soil and water salinity; and (g) non-standard and sub-optimal cropping practices. In addition, the $K_c$ was extended to natural vegetation to support hydrologic applications. FAO56 produced a range of practical guidelines describing how the referred effects can be integrated into the single $K_c$ crop coefficient that incorporates both crop transpiration and soil evaporation processes, or into the dual $K_c$ crop coefficient that separates these two processes.

The $K_c$ curve is constructed to be a visual and simple tool that displays the impacts of trends and controls by a specific crop to modify the ET estimated by the reference crop. The many examples of its application prove that when appropriate crop and weather data are used, the $K_c$ curve is accurate not only for practical but also for research purposes as demonstrated by numerous research papers and application studies referred to throughout this paper and by a variety of reviews including Burt et al. (2005) and Farahani et al. (2007).

The computational procedures presented in FAO56 have greatly facilitated the development of transferrable computer models for water management and planning that can be applied with a reasonably limited amount of local information and that allow simulation and evaluation of crop water response under a range of conditions and practices. One of the early examples of an integrated approach of a computerized crop water management model has been FAO CROPWAT, first published in 1992 as FAO Irrigation and Drainage Paper No 46 (Smith, 1992), and widely used by engineers, agronomists and students for irrigation management and planning. The CLIMWAT database (FAO Irrigation and Drainage Paper No 49, Smith, 1993) contains mean monthly climatic data assembled by FAO from 146 countries. That database supported the ready use of CROPWAT for planning studies aimed at both rainfed and irrigated crop production (Smith, 2000). Recent versions of CROPWAT and CLIMWAT can be downloaded from the FAO website (Smith, 2008a,b). Some expansion of the FAO $K_c$ database traceable to FAO24 and FAO56 was made in Chapter 5 of *Irrigation* (Allen et al., 2011c) and in Chapter 8 of the ASABE *Design and Operation of Farm Irrigation Systems* (Allen et al., 2007a), as well as in the *Traité d'irrigation* (Pereira et al., 2006). Additional expansion relative to fruit trees and vines was made in Allen and Pereira (2009).

The concept of reference evapotranspiration and crop coefficient curve, where the crop coefficient curve requires knowledge of only three $K_c$ values defining the initial, mid-season and end-season periods, produces a consistent and solid foundation for ET estimation that practicing professionals will likely continue to use for some time. The $K_c$–$ET_{ref}$ approach will continue to evolve in the future, with further developments including applications with national and global data sets, including gridded weather and soils data. The approach may ultimately be replaced by more complicated and packaged ET estimation systems. However, it will probably continue to be used as a comparative basis for quality assurance/quality control (QA/QC) purposes.

The following sections provide further detail on the background, principles and procedures of FAO56, in the context of recent advances in research, with some elaboration on merits and shortcomings.

## 2. Reference evapotranspiration

### 2.1. Background and adopted approach

According to Burman et al. (1980), the definition of $ET_{ref}$ is traceable to Jensen et al. (1970) who stated: "the upper limit or maximum evapotranspiration that occurs under given climatic conditions from a field having a well-watered agricultural crop with an aerodynamically rough surface such as alfalfa with 12 in. to 18 in. of top growth". Doorenbos and Pruitt (1975, 1977) adopted a different definition that is effectively the basis of the definition adopted in FAO56 and that utilizes clipped, cool season grass as a reference: "the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water". Basic concepts for reference ET estimation have continued to be discussed in international forums, for example, by the International Commission on Irrigation and Drainage (ICID) (Perrier, 1978), with standardization of definitions discussed and first adopted at the Paris meeting of ICID in Perrier (1985).

Numerous equations were in use for estimating reference ET through the 90s, with large number of studies and research on selecting or calibrating a reference or so-called potential ET[2] equation (Jensen et al., 1990). Equations included various formulations of the Penman combination equation (Penman, 1948), the equations adopted in FAO24 that consisted of adaptations of the Penman, Makkink, Blaney Criddle and pan evaporation methods (Doorenbos and Pruitt, 1977), and a range of empirical and regression methods. A comparative assessment of about 20 common methods was produced by Jensen et al. (1990) which provided good evidence that a single, physically-based method could and should

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[2] The term "potential ET" was once used, in the 1960s through 1970s, to represent a condition of maximum ET from a wet surface. Its use was often interchanged with that of the reference crop. However, the parallel usage of the potential ET term to represent maximum ET from any specific crop type under nonstressed conditions has caused substantial confusion within the ET communities. As a result, many professional societies and organizations such as the American Society of Civil Engineers, American Society of Biological and Agricultural Engineering, ICID and FAO have advocated, since the 1980s, to reserve the use of the term "potential ET" to represent the ET rate from any nonstressed crop and to use the term "reference ET" when referring to a maximum or near-maximum, standardized index of weather and climate-driven and controlled ET (Allen, 2005). This usage was adopted by FAO24 and FAO56. In situations where crop development is low and less than the full ground surface is covered by vegetation, potential crop ET will often be less than reference ET. In situations where crop development is advanced and most of the ground surface is covered by vegetation, potential crop ET will often exceed the grass-reference ET. Nevertheless, the term "potential ET" continues to be frequently and ambiguously used in hydrology and climate studies. It is used here only to provide context for the reference ET definition.

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be adopted to represent reference ET. That suggestion encouraged the efforts by ICID and FAO to standardize a single reference ET method, leading to the publication of FAO56.

The FAO version of the Penman–Monteith equation for estimating $ET_{ref}$ was first presented and recommended in the FAO Report of the Expert Consultation on Procedures for Revision of FAO Guidelines for Prediction of Crop Water Requirements (Smith et al., 1991, 1992). The Expert consultation of 1990 brought together a unique group of high-level experts, including W. Pruitt, M. Jensen, J.L. Monteith, J. Doorenbos, R. Feddes, A. Perrier and others who, based on comparative analyses and research advances then available, recommended the adoption of the Penman–Monteith (PM) equation for estimating $ET_{ref}$ and the utilization of standard values for a hypothetical grass reference surface having an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m$^{-1}$ and an albedo of 0.23. Those definitions enabled the parameterization of the Penman–Monteith equation to produce a standardized grass crop reference ($ET_o$) equation, generally referred to as the FAO–$ET_o$, the FAO–PM or the PM–$ET_o$ equation. The computation of parameters in the PM equation was also standardized. The general updated definition and computation procedures were first published in Allen et al. (1994a,b) and presented to a worldwide conference on evapotranspiration in Allen et al. (1996), Pereira et al. (1996), Smith et al. (1996). The PM–$ET_o$ was generally well received by the scientific and engineering communities who readily adopted the novel and standardized equation, with feedback from these communities later considered when producing the FAO56 guidelines.

The philosophy of FAO and advisors in selecting the PM method as a globally applicable reference method was that “physics are physics everywhere”. Thus, if the primarily physics-based PM method is set up correctly using high quality ET measurement data from a handful of locations, it should sufficiently serve as a basis for crop ET globally. This has largely been born out by comparative studies of PM–$ET_o$ and local ET measurements, e.g., Todorovic (1999), Ventura et al. (1999), Wright et al. (2000), Itenfisu et al. (2003), Lecina et al. (2003), Steduto et al. (2003), Garcia et al. (2004), Berengena and Gavilan (2005) and Allen et al. (2006). Various sensitivity analyses and regional studies confirm applicability to a large variety of environments (Gong et al., 2006; Nandagiri and Kovoor, 2006; Estévez et al., 2009; Ye et al., 2009).

Following the lead of FAO and national and international discussions on merits of adopting a taller reference crop in addition to clipped grass (Pereira et al., 1999), ASCE standardized the Penman–Monteith equation for both clipped grass and alfalfa surfaces and adopted similar parameterizations as FAO for computation of equation components. The result was the ASCE–PM $ET_{ref}$ equation (ASCE-EWRI, 2005). A formulation of the ASCE–PM ETo equation was defined for hourly calculations using different surface resistances for daytime and nighttime, respectively, compared to the 24-h timestep, where a lower $r_s = 50$ s m$^{-1}$ value for the clipped-grass reference was recommended for daytime and $r_s = 200$ s m$^{-1}$ was recommended for nighttime, based on a number of research results (Allen et al., 2006). Adopting the small value for daytime $r_s$ was in agreement with previous studies comparing variable vs. fixed $r_s$ (Todorovic, 1999; Lecina et al., 2003; Steduto et al., 2003) and was advocated by Allen et al. (2006) for application of the FAO–PM method. The reference ET then became, for application to both 24-h and hourly or shorter timesteps (ASCE-EWRI, 2005; Allen et al., 2006, 2007a):

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma\left(C_n/T + 273\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad (1)$$

where $ET_{ref}$ is the standardized reference ET for clipped grass ($ET_o$) or alfalfa ($ET_r$) surfaces, mm d$^{-1}$ for daily time steps, or mm h$^{-1}$ for hourly or shorter time steps; $R_n$ is the calculated net radiation at the crop surface, MJ m$^{-2}$ d$^{-1}$ for daily time steps, or MJ m$^{-2}$ h$^{-1}$ for hourly or shorter time steps; $G$ is the soil heat flux density at the soil surface, MJ m$^{-2}$ d$^{-1}$ for daily time steps, or MJ m$^{-2}$ h$^{-1}$ for hourly or shorter time steps; $T$ is the mean daily or hourly air temperature at 1.5 to 2.5 m height, °C; $u_2$ is the mean daily or hourly wind speed at 2 m height, m s$^{-1}$; $e_s$ is the saturation vapor pressure at 1.5 to 2.5 m height, kPa, calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature and for hourly time steps using hourly average air temperature; $e_a$ is the mean actual vapor pressure at 1.5 to 2.5 m height, kPa; $\Delta$ is the slope of the saturation vapor pressure-temperature curve, kPa °C$^{-1}$; $\gamma$ is the psychrometric constant, kPa °C$^{-1}$; $C_n$ is the numerator constant that changes with reference type and calculation time step, K mm s$^3$ Mg$^{-1}$ d$^{-1}$ or K mm s$^3$ Mg$^{-1}$ h$^{-1}$; $C_d$ is the denominator constant that changes with reference type and calculation time step, s m$^{-1}$.

Values for parameters $C_n$ and $C_d$ are given in Table 1.

The coefficients in Table 1 for the ASCE-EWRI (2005) clipped grass reference exactly replicate the FAO–PM definition for 24-h timesteps, and replicate the FAO–PM definition for hourly timesteps as redefined by Allen et al. (2006). These new approaches to define reference ET have been well received by the communities of ET users and researchers, especially those in the agricultural domain. As an indication of acceptance, references to the PM–$ET_o$ have appeared in more than 11,500 citations in research articles, including journals of hydrology, agricultural water management, agronomy, water resources engineering and management, meteorology, and climate and environmental research.

One of the significant considerations that went into the selection and definition of the Penman–Monteith (PM) equation as the representation and definition of the clipped grass reference was its need to function as the single reference basis for FAO56 (Smith et al., 1992). The adoption of the PM equation and single reference basis has effectively and substantially reduced the many discussions and research efforts of the past on development and selection of ET reference crop methods and has established one worldwide, accepted, and now largely uncontested, procedure to estimate reference crop evapotranspiration. In essence, the adoption of the single reference method and the use of the PM equation to define that reference, hypothetically, made its ‘validation’ or ‘improvement’ by researchers around the globe much less necessary. Thus, valuable researchers have been freed to conduct research on water requirements of important local crops, rather than getting mired in studying, developing or validating the reference crop. In the opinion of FAO, this is a much more effective and judicious use of research efforts and has led to development of substantially improved water management and increased food production globally. The FAO Penman–Monteith method has become a de-facto international standard method for reference evapotranspiration.

### 2.2. Future usage of $ET_{ref}$

The use of $ET_{ref}$ as the basis for practical estimation of $ET_c$ is expected to continue because of its current widespread use and acceptance, and the consistent and relatively good performance afforded by defining $ET_{ref}$ and standardizing parameters based on the Penman–Monteith method as set forth in FAO56 and continued by ASCE-EWRI (2005). This is especially true when considering inaccuracies, limited availability and uncertainties inherent in much of the historical and current weather measurements and cropping and irrigation information. These shortcomings will continue to hamper widespread application of more complex and descriptive applications such as the direct application of the PM method to cropped surfaces and multi-layer approaches.

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**Table 1**
Values for $C_n$ and $C_d$.

| Calculation timestep | Short reference, $ET_o$ (clipped grass) | | Tall reference, $ET_r$ (alfalfa) | | Units for $ET_o$, $ET_r$ | Units for $R_n$, $G$ |
|---|---|---|---|---|---|---|
| | $C_n$ | $C_d$ | $C_n$ | $C_d$ | | |
| Daily | 900 | 0.34 | 1600 | 0.38 | $\mathrm{mm\,d^{-1}}$ | $\mathrm{MJ\,m^{-2}\,d^{-1}}$ |
| Hourly during daytime | 37 | 0.24 | 66 | 0.25 | $\mathrm{mm\,h^{-1}}$ | $\mathrm{MJ\,m^{-2}\,h^{-1}}$ |
| Hourly during nighttime | 37 | 0.96 | 66 | 1.7 | $\mathrm{mm\,h^{-1}}$ | $\mathrm{MJ\,m^{-2}\,h^{-1}}$ |

$ET_{ref}$, in particular $ET_o$, will continue to be used to characterize the local climate or as a component of drought indices where $ET_o$ is contrasted with precipitation (e.g., Dai, 2011; Paulo et al., 2012) or where anomalies in $ET_o$ are used to indicate the onset of flash droughts (McEvoy et al., 2012). Although some climate studies use the term "potential ET" in place of "reference ET", ambiguity of what "potential ET" means would be reduced by more extensive definition of potential ET as potential crop ET or by using one of the reference crop ET definitions.

### 2.3. *Multiple ET references*

The utility of adopting multiple reference crops was discussed by Pereira et al. (1999), considering theoretical advantages of selecting reference crops having similar aerodynamic properties to the crops being considered, including the production of smaller and more readily recognizable variation in $K_c$. On the other hand, in practice, multiple reference crops can complicate the operational use of the $K_c$–$ET_{ref}$ two-step approach, where multiple 'families' of $K_c$ curves are required, and where adjacent or competing political jurisdictions may select a different reference crop basis. This is often common in the USA.

Historically, the two common vegetation types used to define and represent the reference ET estimate have been the clipped, cool season grass and the full-cover alfalfa crop. The clipped, cool season grass reference, termed $ET_o$, has been the principal $ET_{ref}$ method due to its early adoption in FAO24 and the ability to cultivate this reference across a wide range of locations and climates. The alfalfa reference ET, termed $ET_r$, can be argued to have the advantage of better representation of the upper limit of expected ET from extensive surfaces of vegetation, such as from agricultural fields. The better representation of maximum ET stems from the taller 0.3 to 0.7 m height of full-cover alfalfa, averaging 0.5 m, as compared to the typically 0.08 to 0.15 m height of clipped grass, averaging 0.12 m, and from the higher leaf area of alfalfa, the generally higher leaf conductance of alfalfa and the higher tolerance by alfalfa to effects of evaporative water demand or reduced soil water content on reducing ET rates, as compared to the grass reference (Allen et al., 1989; Pereira et al., 1999; ASCE-EWRI, 2005). The higher $ET_{ref}$ rates by alfalfa tend to produce maximum $K_c$ values that approach, and are generally limited by 1.0. This serves as a useful means to assess bias in reported $K_c$ data (Allen et al., 2011a). However, grass is much more often used as a reference crop than alfalfa, and $K_c$ available for the latter are more limited than for grass. The ASCE-EWRI publication provided standardization of parameters for alfalfa $ET_r$.

A drawback of the continuation of two classes of $ET_{ref}$ is the need for two classes of $K_c$. $K_c$ for the alfalfa reference are generally 0.7 to 0.8 as large as that for the $ET_o$ basis due to the larger magnitude of $ET_r$. $K_c$ based on $ET_r$ are generally more consistent in value over ranges in climate due to the closer similarity of agricultural crops to the alfalfa reference in terms of height, leaf area and stomatal conductance (Allen et al., 2007a). The use of two $K_c$ bases does provide opportunity for comparing $K_c$'s derived from different sources to determine expected error and impacts of the geographic source of data and cultivars represented.

### 2.4. *Hourly vs. daily calculation time steps. Future issues in $ET_o$ use and calculation*

The FAO56 and ASCE-EWRI (2005) standardizations support both 24-h and hourly or shorter calculation time steps for $ET_{ref}$ (Eq. (1)). A comparison between both methods was analysed by López-Urrea et al. (2006). The 24-h calculation time step has proven to be relatively consistent and accurate for estimating reference ET (Doorenbos and Pruitt, 1977; Jensen et al., 1990; ASCE-EWRI, 2005) and many lysimeter based studies have used the 24-h time step as a basis for calibration or verification of reference ET methods. The general consistency and accuracy of the PM method for 24-h time steps speaks to the combination equation's robustness in estimating evaporative behavior given a particular set of meteorological conditions.

The standardized PM method applied daily is considered to be accurate and dependable during growing periods. The hourly calculation time step, however, because it keeps radiation and aerodynamic parameters synchronized in time, is considered to be more dependable and accurate in simulating the ET conditions represented by the standardized definitions under conditions where wind speed, solar radiation and vapor pressure deficit are not in proximate time synchronization during the day. The use of hourly calculation time steps calculates the energy balance process more accurately than 24-h time steps during times of the year when daylength is relatively short, such as during winter. During these times, some of the compensating assumptions in the procedures for applying the combination method on a 24-h time step may break down (Allen et al., 2006).

Application of ET equations over only daytime periods (i.e., ignoring calculations during nighttime) is discouraged. This practice ignores any ET that may occur during nighttime and that can be as much as 15% of 24-h ET in arid and semiarid climates (Tolk et al., 2006). In addition, application of the combination or energy balance equation for a daytime period, only, requires estimation of a daytime average value for soil heat flux, G, which cannot be assumed zero as it generally can for 24-h calculation time steps.

Values calculated for reference ET for nighttime hours occasionally take on negative values. The user may feel compelled to set negative values to zero before summing over the 24-h period. However, in some situations, negative hourly computed $ET_{ref}$ may indicate some condensation of vapor during periods of early morning dew and should therefore be registered as negative during the summing of 24-h ET. In other situations, negative hourly $ET_{ref}$ during nighttime reflect the uncertainties in some parameter estimates including $R_n$ and assumptions implicit to the combination equation, and represent some of the random variation of ET estimates about a mean value that may be zero during some nighttime periods. These random, negative ET estimates should be retained in the 24-h sum to counterbalance random, positive ET estimates during the same nighttime period (Irmak et al., 2005; Allen et al., 2006). In general,

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the impact of negative hourly values on ET summed over daily periods is usually less than a few percent.

### 2.5. Weather data quality assessment

The application of the PM–$ET_o$ equation has two main requirements: that computation of the parameters follow standardized procedures as proposed in FAO56 guidelines, and that weather data are of good quality and represent weather conditions to be found over a green grass area, consistent with the $ET_o$ definition. FAO56 was perhaps the first international publication on ET to place strong emphasis and encouragement for weather data quality assessment and control (QA/QC). Accurate estimation of $ET_o$ requires accurate and representative weather data. Combination equations including the PM equation can be relatively sensitive to error in weather data, with the degree of sensitivity changing with time of year and climate. During summer, solar radiation can dominate the ET estimate, especially in humid and sub-humid climates, where the relative power of the vapor pressure deficit and wind term of the PM is small relative to the radiation term. During wintertime, if solar radiation is low, wind speed and vapor pressure deficit can be strong drivers of the ET calculation. Error in wind speed and vapor pressure deficit can dominate in arid and semiarid climates during summer. Ley et al. (1994) analyzed sensitivity of the 1982 Kimberly version (Wright, 1982) of the Penman equation in semi-arid climates and found 24-h $ET_{ref}$ estimates to be most sensitive to combined error in daily maximum and minimum air temperatures, followed by error in daily maximum air temperature, solar radiation, dew point temperature, wind speed, and daily minimum air temperature. In general, sensitivity coefficients for $ET_{ref}$, defined as the percentage change in $ET_{ref}$ per percentage change in the variable, were less than 1.0 (Ley et al., 1994), which suggests that $ET_{ref}$ estimates were somewhat robust to error in weather data. However, the relative sensitivity of any one variable is impacted by the strength of the other weather variables. Gong et al. (2006) evaluated a 41-year record of daily weather data at 150 national meteorological observatory stations in China and found that the PM–$ET_o$ was most sensitive to relative humidity, followed by shortwave radiation, air temperature and wind speed, with rank of the four climatic variables varying with season and region, and impacted by regional wind-speed patterns. The needs for checking the quality of weather data and approaches for their correction are discussed by Allen (1996, 2008), Jensen et al. (1997) and Estévez et al. (2011) among others.

Weather data should be screened before use in an $ET_{ref}$ equation to ensure that the data are of good quality and are representative of well-watered conditions. This is especially important with electronically collected data, since human oversight and maintenance may be limited. Meteorological services should perform QA/QC of their data (Feng et al., 2004; ASCE-EWRI, 2005). When weather measurements are determined to be faulty, they can be adjusted or corrected using a justifiable and defensible procedure, or the user may elect to replace perceived faulty data with estimates. FAO56, followed by ASCE-EWRI (2005), presented general, graphics-based procedures for straightforward assessment of integrity and representativeness of weather data used for $ET_{ref}$ calculation. Procedures were also recommended in FAO56 for correcting and/or estimating data in situations where data are shown to be of poor quality or are missing.

Importance of the weather station location was emphasized in FAO56. When making calculations of $ET_{ref}$, weather measurements should reflect the environment that is defined by the reference surface. This is important because most reference ET equations were developed for use with meteorological data collected primarily over and downwind of dense, fully transpiring grass or similar vegetation exhibiting behavior similar to the definition of the reference surface condition. Feedback exists between the boundary layer above the surface and the surface, so that the energy balance and evaporation at the surface impacts temperature and humidity of the air layer above. Weather stations supporting the calculation of $ET_{ref}$ should measure temperature, humidity and wind speed within the dynamic boundary overlying the ground surface (Allen et al., 2011a,b). Properties of this boundary layer characterize the energy balance at the surface and are used to estimate the ET rate.

Studies in southern Idaho, USA, by Burman et al. (1975) and De Bruin et al. (2005), and modern blending height/profile theory models, for example, by Chen and Dudhia (2001), have shown humidity, temperature and wind speed levels in the lower levels of the atmosphere to change substantially when going from desert to areas containing irrigated fields. Ideally, weather stations should be centered within large, nearly level expanses of uniform vegetation that are supplied with sufficient water through precipitation and/or irrigation to support ET near maximum levels. The preferred vegetation for a weather site is clipped grass due to the practical reasons for consistent site maintenance. However, alfalfa or a grass-legume pasture maintained at a height of less than about 0.5 m may also serve as an effective vegetation for the site (ASCE-EWRI, 2005) without impacting the wind speed measurement. Meteorological measurements made over other short, green, actively transpiring crops will approach reference measurements, provided canopy cover exceeds approximately 70%. In an ideal setting, the well-watered vegetation extends at least 100 m in all directions from the weather station. However, it is recognized that frequently such a weather station site is not available, and that often some non-vegetated areas or roadways will be present near the station. Allen (2008) summarized a source-area footprint approach to estimate the impact on weather measurements of a local area of dryness in the immediate vicinity of a weather station having transpiring vegetation further upwind, and vice-versa. That approach can be used to assess whether the size of a patch of bare or dry ground surrounding a weather station, for example, in the corner of a center pivot irrigated field, is large enough to impact the temperature and humidity measurements by more than some fixed percent. It can also be used to indicate whether a small patch of well-watered vegetation surrounding a weather station is sufficiently large to affect the near surface boundary layer measured by the weather station so that it represents 'reference' conditions.

Temperature corrections to overcome problems of local advection and dryness of weather station settings were explored by Allen (1996) and Temesgen et al. (1999). When weather data are not from an agricultural or reference environment and are shown to be substantially affected by the lack of local ET, the user should be willing to adjust the data using procedures, for example, from FAO56, ASCE-EWRI (2005), or Allen et al. (2007a), or to abandon the use of the data. Future research can focus on the quality requirements of observation facilities and data control (Allen, 1996, 2008; Allen et al., 2011a,b) because of the negative influences that poor data have on estimates of $ET_o$, particularly in arid and semi-arid regions where local advection and aridity of the weather data collection site may play a substantial role.

### 2.6. Alternative computation procedures

Error may result from deviation from standardized methods for computing parameters in the PM–$ET_o$. The procedures proposed by FAO56 guidelines should be followed. Various types of alternative procedures have been tested by Nandagiri and Kovoor (2005), who showed the need for strict adherence to the FAO56 recommended parameter computation procedures, especially for estimating vapour pressure deficit and net radiation parameters. Results of studies by Yoder et al. (2005) and Irmak et al. (2011) are in agreement with those findings. Gavilán et al. (2007) reported on

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the importance of using the FAO56 procedures when computing net radiation.

In many countries, measured weather data are not accessible without payment, which may be expensive, thus leading users to explore computing $ET_o$ using alternative estimation methods, such as using temperature data only. However, FAO56 recommended against the 'retreat' to a more simple $ET_o$ equation. Instead, FAO56 recommended estimating missing data and retaining the use of the PM method. The retention of the PM–$ET_o$ method, in spite of data scarcity, and estimating missing data rather than modifying the basic method itself or fitting methods to data, was the intent of FAO in adopting the single, physically based PM method, and it has been largely successful. Significant recent research on reference ET has focused on solutions to difficulties in computing PM–$ET_o$ created by the lack of full data sets (Allen, 1995, 1997; Allen et al., 1998; Liu and Pereira, 2001; Droogers and Allen, 2002; ASCE-EWRI, 2005; Popova et al., 2006a; Jabloun and Sahli, 2008; Trajkovic and Kolakovic, 2009; Gocic and Trajkovic, 2010; Huntington and Allen, 2010; Martí et al., 2011; Todorovic et al., 2013; Raziei and Pereira, 2013a,b; Huntington et al., 2014), or on filling gaps in existing data sets. Many of the methods in the cited references, including FAO56, produce reliable estimates for missing weather data, and the retention of the PM–$ET_o$ method retains the physical basis for calculation and interactions among weather parameters.

A large number of publications have reported on the testing of alternative equations against PM–$ET_o$ as computed with full weather data sets (Hargreaves and Allen, 2003; Droogers and Allen, 2002; Chen et al., 2005; Adeboye et al., 2009; Sentelhas et al., 2010; Raziei and Pereira, 2013a,b; Todorovic et al., 2013 and others). In many cases, this research has been of a statistical nature only, mostly aiming to derive simplified computational tools that produce results similar to PM–$ET_o$. Conceptual aspects supporting the retention of the PM–$ET_o$ equation have often not been taken into consideration and many studies have tended to overlook that, although the PM–$ET_o$ equation is a physically-based combination equation that defines the ET of a reference crop, provision was made in FAO56 to apply the PM equation using measured air temperature data only. Under data-limited conditions, preferences have frequently been directed toward the Hargreaves–Samani (HS) equation (Hargreaves and Samani, 1985), which requires air temperature only and is easier to compute than PM–$ET_o$ (e.g., Hargreaves and Allen, 2003; Buttafuoco et al., 2010). Some studies (Sperna-Weiland et al., 2012) have concluded that such approaches may be considered accurate enough for hydrological purposes. However, much of time, the application of the HS method is done without sufficient attention to the need to review and revise coefficients in the method, particularly the radiation adjustment coefficient $k_{Rs}$, which is included in the bulk numerical coefficient (0.0023) of the HS equation, and without appreciation for the impact of wind speed on $ET_o$. The PM–$ET_o$, when applied using only measured temperature data (referred to as PMT), retains many of the dynamics of the full data PM–$ET_o$ (Hargreaves and Allen, 2003; ASCE-EWRI, 2005; Trajkovic and Kolakovic, 2009). The PMT requires a somewhat heavier computation and data preparation than the HS method. However, this should not be an issue with today's computers and computational code. Computer code is typically developed one time and used many times. The PMT has been demonstrated to produce low errors of estimate if, like the HS, a calibrated $k_{Rs}$ is used to estimate solar radiation (Raziei and Pereira, 2013a,b; Todorovic et al., 2013), or even the Thornton and Running (1999) method (Allen and Robison, 2007, 2009; Huntington et al., 2014), and if temperature is adjusted to overcome the effects of site aridity. Recently, a new procedure has shown promise for estimating actual vapour pressure in humid climates by estimating the dew point temperature from a value near the average temperature rather than from minimum temperature as proposed in FAO56 (Raziei and Pereira, 2013a,b; Todorovic et al., 2013).

The search for solutions for obtaining PM–$ET_o$ in the absence of full data sets (solar radiation, air temperature, humidity and wind speed) has led to the development of a variety of approaches including the use of generated weather data (Stöckle et al., 2004) and, more often, replacement equations to the FAO–PM based on artificial neural networks (ANNs), fuzzy and neuro-fuzzy systems, genetic algorithms, and multiple regression analyses (e.g., Kişi and Öztürk, 2007; Parasuraman et al., 2007; Jain et al., 2008; Partal, 2009; Shiri et al., 2012; Kişi and Cengiz, 2013; El-Shafie et al., 2013). These algorithms have generally been calibrated with or compared to $ET_o$ computed using the FAO–PM. Users of these algorithms need to consider that many trends defined by these approaches remain empirical and may not translate well in time and space. There is no replacement for basic physics, as represented in the PM–$ET_o$ formulation, and the estimation of individual weather inputs to the PM equation has the merit of allowing explicit review of the estimates and their accuracies prior to computations (Allen et al., 1998; Hargreaves and Allen, 2003; ASCE-EWRI, 2005).

Martí and Zarzo (2012) used principal components analysis (PCA) for $ET_o$ estimation using exogenous $ET_o$ records from other stations that function as ancillary data suppliers. Other attempts used daily weather forecast messages (Cai et al., 2007, 2009) or full reanalysis weather data sets to estimate $ET_o$ (Ishak et al., 2010; Sperna-Weiland et al., 2012; Raziei et al., 2013; Srivastava et al., 2013). A major difficulty with many of the gridded weather data sets produced by general circulation and weather forecasting-type models is inaccurate estimation of wind speed (Ishak et al., 2010, 2013; Huntington et al., 2014). Absence of irrigation inputs causes generated weather data over irrigated regions to often be much hotter and drier than actual due to the lack of conditioning feedbacks between evaporation and near surface air layers.

Recent interpolation techniques consider effects of elevation on $ET_o$ and create gridded weather data that extend full data sets and point-based weather measurements to estimate FAO–$ET_o$ in new locations (Mardikis et al., 2005; McVicar et al., 2007). Kilic et al. (2014) have evaluated interpolation of weather data prior to calculation of $ET_o$ vs. calculation of $ET_o$ at point locations and then interpolating. They concluded that calculation of $ET_o$ first and then interpolating was computationally more efficient and more integrative of the weather factors influencing $ET_o$. Mapping $ET_o$ using remote sensing data can also be used in combination with interpolation of ground observations of weather data (Hart et al., 2009). Recently, ANNs and multiple linear regressions have been developed as alternatives to temperature based methods to compute and map $ET_o$ from full data sets ($R_s$, $T$, $R_H$ and $U$) observed at exogenous point locations to gridded surfaces (Martí et al., 2011; Cristea et al., 2013).

Recent approaches were developed to estimate $ET_o$ from remotely sensed data. Bois et al. (2008) used HelioClim-1 solar radiation data. More recently, De Bruin et al. (2010, 2012) adopted a radiation-temperature equation based on the Makkink equation to estimate daily $ET_o$ using radiation data from a geostationary satellite, the Satellite Application Facility on Land Surface Analysis (LANDSAF). An improvement was achieved using satellite temperature data in addition to radiation (Cruz-Blanco et al., 2014). Currently available results for Andalusia, southern Spain, and Portugal that have adopted locally calibrated adjustment factors for radiation and temperature are quite promising.

## 3. Crop evapotranspiration

The crop coefficient–reference ET concept was first fully implemented by Jensen (1968) by relating ET for a given crop over a

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specific period of days to weeks to the so-called "potential ET", defined in Jensen (1968) as the rate of ET from a well-watered crop having an aerodynamically rough surface like alfalfa with 0.3–0.5 m of top growth. This ratio, termed the crop coefficient, $K_c$, followed the approach proposed by van Wijk and de Vries (1954). The $K_c$ was stated to represent "the combined effects of resistance to water movement from the soil to the evaporating surfaces, resistance to diffusion of water vapor from the evaporating surfaces through the laminar boundary layer, resistance to turbulent transfer to the free atmosphere, and relative amount of radiant energy available as compared to the reference crop" as reported in a historical review by Jensen (2010). The concept of potential ET evolved into that of reference ET, by assuming alfalfa as the reference as done by Jensen and others (Wright, 1982) or by assuming clipped, cool-season grass as the reference by Pruitt and Doorenbos (1977). Wide international usage of the $K_c$–$ET_{ref}$ approach occurred following publication of FAO24 where the grass reference was adopted and substantial information on crop coefficients relative to the grass reference was tabularized (Doorenbos and Pruitt, 1975, 1977).

### 3.1. Single crop coefficients

The single crop coefficient ($K_c$) of FAO56 closely follows the time-durable approach introduced globally in FAO24 (Doorenbos and Pruitt, 1977) where the $K_c$ 'curve' was presented as a series of four linear segments representing the initial, development, midseason and late season crop growth periods. This simplified definition of crop growth in FAO24 and FAO56 has been readily accepted by users and researchers, with the understanding that the linear curve segments are approximate averages of trends in $K_c$ over time and are generally within error and uncertainty in ET measurements and in application-to-application variability (Allen et al., 2011a). It is also understood that tabularized values in FAO24 and FAO56 for lengths of crop growth stages are illustrative of general tendencies, but that local observation is definitely required to account for variation in local crop variety, in cultural practices and in year-to-year variation in weather effects. However, many users inappropriately assume tabularized lengths of crop growth stages as universally applicable, creating an unnecessary source of error that the same authors often attribute to insufficiencies in FAO56. However, FAO56 and follow on publications, e.g., Allen et al. (2007a), have emphasized the need to observe and establish local cropping dates.

In many cases, the emergence of vegetation, greenup, and attainment of effective full cover can be estimated using cumulative degree-based regression equations or plant growth models (Sinclair, 1984; Sammis, 1985; Ritchie and NeSmith, 1991; Slack et al., 1996; Snyder et al., 1999; Cesaraccio et al., 2001; Ojeda-Bustamante et al., 2004; Allen and Robison, 2007; Martínez-Cob, 2008; Ceglar et al., 2011; Ghamarnia et al., 2013; Payero and Irmak, 2013). The use of cumulative growing degree days provides a quantitative stretching or shrinkage of the generated $K_c$ curves for years or growing seasons that run cooler or warmer than average. This approach is required for prospective studies of climate change impacts on crop water and irrigation requirements, e.g. studies in this issue as that by Saadi et al. (2014) and a US study by Huntington et al. (2014).

In FAO56, $K_c$ values from FAO24 were readjusted to work with the defined PM–$ET_o$ and new $K_c$ values were reported for additional crops. A further development in FAO56 was the replacement of four columns of values in FAO24 for the $K_c$ during midseason, $K_{cmid}$, and $K_c$ at the end of the late season, $K_{cend}$, with a single column of $K_c$ values standardized for a single climate defined as one having an average daily minimum relative humidity of 45% and wind speed of 2.0 m s$^{-1}$. An equation was presented in FAO56 to adjust tabularized $K_{cmid}$ and $K_{cend}$ for impact of deviation of the general climate from the defined climate, primarily in proportion to average daily minimum relative humidity and wind speed. The adjustments consider the influence of crop height on the relative impact of weather on $K_c$ and improve the transferability of a single set of tabularized $K_c$ from one climate to another. The adjustments largely reproduce the four columns of FAO24.

### 3.2. Transferability of single crop coefficients

A major departure of FAO56 from FAO24 was, for transferability purposes, the adoption of the concept of standard, optimal crop conditions as the basis for tabularized $K_c$; hence $K_c$ and $ET_c$ in FAO56 represent ET rates under optimal, well-watered conditions. In the field and in common practice, crop conditions are often not optimal due to insufficient or nonuniform irrigation, crop density, soil or salinity and agronomic management. $ET_c$ as computed from standardized $K_c$ values is then replaced by the adjusted $ET_{cadj}$, also referred to as actual $ET_{cact}$, and the resulting $K_c$ is either renamed $K_{cadj}$ or $K_{cact}$, or is multiplied by a stress coefficient ($K_s$). Adopting this concept facilitates consistent estimation and transferability of measured and standardized $K_c$; otherwise, it would be necessary to define multiple $K_c$ values for the same crop as has occurred in the past for vines, orchard and other complex crops. The concepts of potential $K_c$ and $ET_c$ and terminology are progressively being accepted by the user communities.

The FAO33 guidelines (Doorenbos and Kassam, 1979) introduced a practical method to estimate yield reductions under conditions of water stress, which was considered in FAO56 to estimate the stress factor $K_s$. In FAO56 $K_s$ is commonly based on soil water stress computations, but was expanded to evaluate reduced crop water use under a wider range of stresses, including salinity stress and to simulate interactions between stress and the soil water balance on a daily basis. The variety of approaches proposed in FAO56 for estimating $K_s$ effectively supports the estimation of $ET_{cadj}$ or $K_{cadj}$, thus contributing to a clearer distinction between local $K_{cadj}$ and standard and transferrable $K_c$.

As noted, the transferability of $K_c$ among climate and locations applies to standard $K_c$, i.e., $K_c$ representing ET from crops cultivated under 'optimal' conditions, and not when crops are stressed or cultivated under sub-optimal conditions, i.e., when the concept of adjusted or actual $K_c$ ($K_{cadj}$ or $K_{cact}$) applies. Some criticism on lack of transferability of $K_c$ stems from authors not appreciating the concepts and physical principles underlying standard vs. actual $K_c$. The theoretical basis and limitations of the standard $K_c$ concept reflect primarily differences in the aerodynamic and surface resistances of the reference crop and of the crop being considered under well-watered conditions, so those differences are influenced primarily by climate (Pereira et al., 1999). This is in contrast to $K_{cadj}$ that may be additionally influenced by unique levels of water or salinity stress or by specific pruning measures, or other cropping practice. These influences cannot be expected to transfer without modification to other locations and they cannot be expected to be standardized. This is the case, for example, for wine grape and olive production, which are often cultivated under water limited conditions. Those conditions and degrees of water stress vary widely, however, so that values for $K_{cadj}$ vary widely. Therefore, those values cannot be standardized, nor directly transferred. Only the unadjusted $K_c$ that represents well-watered conditions can be transferred and used as a basis for adjusting to local conditions of water stress or salinity. Studies by Perrier et al. (1980) and Katerji and Perrier (1983) support the need to distinguish between $K_c$ and $K_{cadj}$ when transferability is considered.

Moreover, $K_c$ values much above those expected when considering the energy available for evaporation continue to be proposed. These unrealistically high values generally result from poor environmental settings and management of vegetation on and surrounding lysimeters, evapotranspiration field estimation

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methods, or soil water balance studies. Allen et al. (2011a,b) recently proposed requirements for appropriate reporting and QA/QC of ET studies and results.

The estimation of $K_c$ for the initial period, $K_{cini}$, was also expanded in FAO56, by considering more soil types and water application characteristics (Allen et al., 2005b). That work leveraged the pioneering work of William Pruitt that was introduced in FAO24. Values for $K_{cini}$, contrary to the $K_c$ for the mid season, $K_{cmid}$, are not transferable because they depend on the frequency and amounts of wettings and on the climate conditioning the evaporation from the soil. As expected, differences found between values locally determined and indicative values tabularized in FAO56 are often large. $K_c$ values for the end season are also often somewhat different from those tabularised due to differences in management and climate.

Feedback from applications indicates that the relatively simple and visual $K_c$ curve approaches of FAO24 and FAO56 are in general confirmed by field observations and are widely accepted (Liu et al., 1998; Tolk and Howell, 2001; Howell et al., 2004; Karam et al., 2005; Lovelli et al., 2005; Popova et al., 2006b; Suleiman et al., 2007; Cholpankulov et al., 2008; Cai et al., 2009; López-Urrea et al., 2009; Popova and Pereira, 2011; Sampathkumar et al., 2013; Zheng et al., 2013). Lower $K_{cmid}$ for actual conditions have also been reported, e.g., Farahani et al. (2008) for cotton, due to partial soil wetting under drip irrigation.

### 3.3. $K_c$ values for new crops and conditions

Since the publication of FAO56, many researchers have reported new $K_c$ values for numerous crops and environments, which are generally close to those reported in FAO56. In addition, $K_c$ for previously unstudied crops such as quinoa and teff have been developed by Garcia et al. (2003) and Araya et al. (2011), for black cumin by Ghamarnia et al. (2013), and for sparse brush vegetation in African highlands by Descheemaeker et al. (2011) where $K_c$ was varied as a function of the respective LAI or the effective ground cover.

New $K_c$ values have been reported for orchard and vine crops, e.g., Orgaz et al. (2006) for olives, Paço et al. (2006) for peaches, and Snyder and O'Connell (2007) for citrus. However, the adoption of the FAO56 $K_c$ approach for trees and vines has faced difficulty in application: the variability of the $K_c$ due to the size of the canopy, the presence of active ground cover or mulch, which can relate to crop spacing, ground shadowing and crop age, and relative amounts of soil evaporation all influence the value for $K_c$ as opposed to that standardized in FAO56. This problem was well identified by Goodwin et al. (2004) and Williams and Ayars (2005) who reported that peach tree and grapevine crop coefficients were linear functions of the shaded area measured beneath the canopy. Focusing on orchards, Allen et al. (2007a) and Allen and Pereira (2009) combined the influence of crop density with standardized values for $K_{cbfull}$, $K_{cmin}$ and $K_{cbcover}$ to compute a $K_{cb}$ for orchards for both bare soil and active ground cover. This modification provided flexibility in adjusting the value for $K_c$ and $K_{cb}$ according to the fraction of ground shaded by canopy, which is highly variable among orchards. This subject is further discussed in the next section.

### 3.4. Dual crop coefficients

The single $K_c$ serves the important purpose of representing averaged $E$ and $T$ from a typical cropped surface for typical frequencies of wetting. However, the single $K_c$ only represents typical conditions that can vary with wetting frequency by precipitation and irrigation and with the type of irrigation practiced. FAO56 therefore introduced the concept of dual crop coefficient, i.e., $K_c = K_{cb} + K_e$, following earlier work by Jensen et al. (1970), Wright (1982) and others, where $K_{cb}$ is the basal crop coefficient representing primarily plant transpiration. $K_{cb}$ also needs to be adjusted for climate as for the single $K_c$, and is also adjusted using $K_s$ for non-standard, stressed, conditions. $K_e$ is the evaporation coefficient that represents the contribution of evaporation from soil to total ET. Calculation of $K_e$ uses a variation on the two stage evaporation model proposed by Ritchie (1972). The appropriateness of this approach has been shown for both field and orchard crops (Allen et al., 2005a; Paço et al., 2012; Zhao et al., 2013; Ding et al., 2013; Wei et al., 2014).

The dual approach improves the accuracy of the ET estimate by improving the accuracy of the evaporation estimate. Kool et al. (2014) reviewed a large number of ET estimation approaches and stressed the importance of partitioning ET for water management purposes. The partitioning ET is also paramount for yield estimation (Steduto et al., 2012; Paredes et al., 2014) where yield is much more closely linked to transpiration than to total ET.

The dual approach generally requires support by a computer model framework because two daily water balances are required, one for the soil evaporation layer and another for the soil explored by the crop roots (Allen et al., 2005a; Rosa et al., 2012a,b). The approach has compared well with field observations for annual crops and for vine and tree crops (Hunsaker, 1999; Tolk and Howell, 2001; Hunsaker et al., 2002, 2003; Howell et al., 2004; Bodner et al., 2007; Greenwood et al., 2009; López-Urrea et al., 2009; Er-Raki et al., 2010; Descheemaeker et al., 2011; Odhiambo and Irmak, 2012; Paço et al., 2012; Zhang et al., 2011; Zhang et al., 2013; Paredes et al., 2014). Extensions allow users to consider the effects of mulches and residue cover (Allen et al., 1998; Rosa et al., 2012a; Ding et al., 2013; Martins et al., 2013) as well as to compute the transpiration of active ground cover crops (Allen et al., 2007a, 2011c; Allen and Pereira, 2009; Fandiño et al., 2012).

The evaporation component of the dual $K_c$ approach was inversely linked to the observation or estimation of the fraction of the ground covered by the crop ($f_c$) in FAO56, where $f_c$ was estimated from $K_{cb}$ to simplify estimation in the absence of field observations of canopy structure. In the dual $K_c$ method, estimation of the fraction of soil wetted ($f_w$) and the fraction of soil wetted and exposed to direct radiation ($f_{ew}$) add accuracy to the estimation of $E$ and total ET (Rosa et al., 2012a,b; Fandiño et al., 2012; Zhao et al., 2013; Paredes et al., 2014). Allen (2011) introduced a 'skin layer' extension to the $K_e$ method to better estimate 'flash' evaporation of small wetting events. That extension brings estimates by the FAO56 $K_e$ technique more in line with estimates by the more physics-based Hydrus model (Šimunek et al., 2005; Allen, 2011). Ultimately, finite element based models such as Hydrus may routinely underlie dual $K_c$ calculations to provide refined estimates of soil evaporation in pre-packaged evapotranspiration models.

Yield relates better to $T$ than to ET (Doorenbos and Kassam, 1979). Therefore, the partitioning of $K_c$ into $K_{cb}$ and $K_e$ produces a ready and relatively simple means for predicting crop yield and water productivity (Paredes et al., 2014). Because of the advantages of partitioning, the dual crop coefficient approach has been adopted by water flux and crop growth models such as SWAT and Hydrus (Ravikumar et al., 2011; Ramos et al., 2012; Xu et al., 2012; Phogat et al., 2013). In some cases, preference is given to two-source resistance-style models for highest accuracy (Jones et al., 2003). Recently, an extensive update of FAO 33 (Doorenbos and Kassam, 1979) was carried out by FAO and published as FAO Irrigation and Drainage Paper No 66 (Steduto et al., 2012). That paper describes the dynamic crop model AquaCrop that builds on FAO56 and adopts a modification of the dual crop coefficient approach where crop growth stages and development of the ET rate are developed on the basis of a crop growth model. The AquaCrop model utilizes some of the conservative approaches of the $K_c$–ET$_{ref}$ approach of FAO56, with enhancements based on biological and phenological principles The complexity involved in crop growth and yield simulation of AquaCrop requires a more detailed parameterization than FAO56 (Raes et al., 2012) to better estimate

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impacts of environmental stresses on crop growth, biomass and yield.

The dual $K_c$ approach of FAO56 has enabled a number of entities to update and revise guidelines on evapotranspiration and irrigation water requirements. For example, the American states of Idaho and Nevada recently revised state-wide estimates of water requirements at more than 100 weather station sites in each state, including first-ever estimates of ET during nongrowing (winter) periods (Allen and Robison, 2009; Huntington and Allen, 2010). These complete-year estimates are valuable in hydrologic studies that require complete water balances. The computation of $ET_c$ during non-growing periods, e.g., during soil frozen periods was improved by the FAO56 procedures and has been shown to perform relatively well (Pereira et al., 2007; Hay and Irmak, 2009; Zhao et al., 2013). The FAO56 dual $K_c$-based approach has been extended to the western half of the US as part of a US Bureau of Reclamation study on future water demands under climate change (Huntington et al., 2014).

### 3.5. ET for non-standard conditions and landscapes

Allen and Pereira (2009) furthered the development of estimation of $K_{cb}$ based on $f_c$ using a density coefficient ($K_d$). That technique permits $K_{cb}$ (and $K_c$) to be computed for a range of row crop, orchard and vine planting densities and canopy sizes, and for when the soil is bare or covered by active vegetation. One objective of the adjustment to $K_c$ and $K_{cb}$ based on vegetation density was to help users of FAO56 methods more readily incorporate impacts of vegetation density into the estimate for the $K_c$ value and to appreciate that 'one size does not fit all' in the case of $K_c$ for orchards and vineyards that can have a broad range of tree size and spacing. Sets of $K_c$ and $K_{cb}$ values for varying densities of orchard and vine crops were computed and tabularized by Allen and Pereira (2009) based on the $f_c$–$K_d$ approach.

FAO56 utilized the concept of the stress coefficient $K_s$ to estimate $ET_{cadj}$ for water stressed crops, including crops subjected to deficit irrigation. $K_s$ is obtained through a soil water balance of the root zone. Importantly, the concept of $K_s$ as applied to water stress was extended to impacts of soil salinity, where both water and salinity stresses were combined. The simple $K_s$ approach of FAO56 has proved to function relatively well (Pereira et al., 2007; Domínguez et al., 2011), although some researchers prefer to use deterministic models that enable them to simulate the dynamics of salt and water flow in the soil profile (Jones et al., 2003; Šimunek et al., 2005; Farahani et al., 2007; Ramos et al., 2012). However, those models are more exigent in terms of parameterization and calibration/validation.

FAO56 introduced relatively simple computation procedures for $ET_c$ under various agronomic management practices, for example, mulches and intercropping. The approaches have performed well over a range of applications, with good results for intercropping (Pereira et al., 2007) and for straw mulching (Martins et al., 2013). Reported results for black plastic mulch have contrasted with FAO56 where Amayreh and Al-Abed (2005) observed $K_{cadj}$ values smaller than proposed in FAO56, whereas Lovelli et al. (2005) reported that FAO56 estimates led to underestimation in $K_{cadj}$. The latter authors also observed the need to adjust crop growth phases due to local temperature effects produced by black plastic mulches.

Allen et al. (2007a, 2011c) reported on extending the dual $K_c$ approach to residential landscape systems to improve the estimate of $K_{cb}$ and $K_c$ as a function of $f_c$ and to incorporate impacts of wetting frequency and managed water stress. $K_{cb}$ and $K_c$ vary widely in landscape settings due to a wide range of mixtures of grasses, trees, shrubs and flowers as well as a wide range in evaporative demands caused by shading of radiation and wind by buildings, local advection of heat from non-evaporating surfaces, and the frequent need for reducing irrigation to implement mild to moderate levels of water stress as a means for water conservation (Nouri et al., 2013). One benefit of employing the $K_c$ approach and basing simple adjustments on $f_c$ is that the process is more visual to the practicing communities of landscape water managers who often do not have substantial backgrounds in evaporation physics. Landscape coefficients are discussed in another paper in this issue (Snyder et al., 2014).

Crop coefficients are typically not readily available for natural vegetation due to the wide range of density, health and water availability to these systems. As a consequence, it is difficult to produce standardized values for $K_c$ that fit even a minority of situations. FAO56 did provide general recommendations on estimating $K_c$ for natural or non-pristine vegetation that are based on plant density, estimated stomatal behavior under well watered conditions, and estimated degree of water stress. An example of application to semiarid natural vegetation in the highlands of northern Ethiopia is reported by Descheemaeker et al. (2011).

### 3.6. ET estimation from remote sensing

FAO56 did not provide specific means for estimating ET from satellite imagery. However, since FAO56 was published, substantial progress has been attained in remote sensing (RS) of ET, which now provides a dependable basis for determining ET by surface energy balance (SEB) and for exploring vegetation indices that can be related to $K_{cb}$. Various review papers focus on the theoretical basis and developments (Glenn et al., 2007; Kilic et al., 2012) and on the applicability of ET derived from RS for irrigation scheduling and advising farmers (Calera Belmonte et al., 2005; D'Urso et al., 2010; Teixeira, 2010).

The most common approaches for ET estimation use vegetation index (VI) approaches or SEB models based on thermal infrared data. Satellite-based SEB models include SEBAL-Surface Energy Balance Algorithm for Land (Bastiaanssen et al., 1998), METRIC-Mapping EvapoTranspiration at high Resolution using Internalized Calibration (Allen et al., 2007b), and TSEB, Two-Source Energy Balance (Kustas et al., 2004). A recent combination of TSEB and a reflectance-based crop coefficient model has been used to estimate soil water content (Neale et al., 2012). The SEB models estimate the ET flux for each pixel of a satellite image using short wave and thermal information. ET is computed as the residual component of the SEB at the time of satellite overpass by subtracting the soil heat flux ($G$) and sensible heat flux ($H$) from the net radiation ($R_n$) at the surface. These models attempt to quantify ET over large areas and over a diverse mixture of crops and landscapes (Santos et al., 2012; Pôças et al., 2013). Using Landsat-scale resolution (30 m) enables the estimation and mapping of ET from individual fields and assessment of variance in ET among populations of fields (Tasumi et al., 2005; Tasumi and Allen, 2007; Singh and Irmak, 2009).

With the VI approach, crop coefficients, both single and dual $K_c$, are estimated from vegetation indices derived from remotely sensed reflectance data, for example, the normalized difference vegetation index (NDVI) or the soil-adjusted vegetation index (SAVI). Because these indices reflect the actual vegetation cover conditions, the estimated $K_c$ or $K_{cb}$ represent $K_c$ or $K_{cb}$ for actual rather than standard vegetation. They should therefore be referred to as $K_{cact}$ and $K_{cbact}$, however many authors have not adopted this conceptual difference. It is important to note that most VI-based methods are unable to observe reductions in $K_c$ caused by acute water or salinity stress. Thermally based methods are required for that reduction.

Numerous examples of VI-based approaches are given in literature for annual and orchard crops, e.g., Bausch and Neale (1987), Calera et al. (2005), Hunsaker et al. (2005), Campos et al. (2010). The VI-based RS approaches are largely based on the fraction of

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ground covered or shaded by vegetation ($f_c$). Remotely-sensed estimates of $f_c$ can be obtained from the NDVI or other vegetation index. Examples are provided by González-Dugo and Mateos (2009) and Johnson and Trout (2012). When $K_{cbact}$ is determined, a parallel modeling approach is required to estimate the soil evaporation coefficient, $K_e$ to produce a total $K_c$ and $ET_c$ estimate (Mateos et al., 2013; Paço et al., 2014). This can be done by integrating the satellite-based information into a water balance model where $K_{cbact}$ is continuously interpolated and $K_e$ is computed separately in real time.

RS-based ET estimation is particularly important for incomplete cover crops such as olive orchards (Santos et al., 2012; Pôças et al., 2014). Remote sensing of vegetation amount provides field-to-field description on the variation of $K_c$ that is created by variation in planting dates, plant spacing and cultivars. Remote sensing of surface energy balance using thermal imagery additionally determines actual $K_{cadj}$ under water stressed conditions. $K_c$'s derived from remote sensing can sometimes be vicariously calibrated or tested by comparing with water balance-based ET estimates at watershed scales, including matching with streamflow records.

$K_c$ databases can be expanded through sampling of $K_c$ produced directly by remote sensing models that employ a surface energy balance to determine ET. The benefit of these methods is that any impact of soil water shortage, salinity or disease is incorporated into the $K_c$ retrieval. It was noted above that these $K_c$ values are the actual, "$K_c$ act", values, rather than the potential, standard $K_c$ values, represented by the published $K_c$ curves. $K_c$ act equals $K_c$ for a given ground cover condition, when there are no stresses. $K_c$ act from energy balance based remote sensing can be compared with $K_c$ estimated from remotely-sensed fraction of cover or vegetation index to estimate reductions caused by water or salinity stress, disease or fertility (Zwart and Bastiaanssen, 2007).

### 3.7. *What has worked well and what will continue to be used*

Conditions that negatively impact accuracy and representativeness of $K_c$ occur readily and are wide-spread. Recommended procedures for assessing the possibility of bias or poor accuracy and integrity of ET and $K_c$ measurements were described in Allen et al. (2011a). Collectors and users of ET and $K_c$ measurement data should always be sceptical of data integrity, regardless of the source. Providers of new ET and $K_c$ information are encouraged to fully document the means of data collection and measurements, provide a full description of the vegetation and water management, and a full description of the associated weather data and $ET_{ref}$ collection. An attempt at describing desired documentation was made by Allen et al. (2011b). The mostly large success of the $K_c$ collections in FAO24 and FAO56 publications stemmed from the bounds placed on $K_c$ values and integrity of procedures for estimating $ET_{ref}$ as begun by W.O. Pruitt in FAO24 and extended in FAO56. Improving the integrity and consistency of $ET_{ref}$ removes biases in developed $K_c$ that stem from use of faulty or biased weather data in the $ET_{ref}$ estimate or a bias in the $ET_{ref}$ estimate itself.

The use of the 'two-stage' method for estimating crop water use, where the crop coefficient is multiplied by an estimate of 'reference' ET ($K_c$–$ET_{ref}$), has the strong advantages of decoupling the (a) majority of day-to-day, weather-driven variation in ET represented by the reference ET, from the (b) day-to-day variation in ET controlled by the specific vegetation and its management.

That decoupling leads to:

a. Helping people new to the field of ET (including policy-makers and students) to visualize and appreciate the impacts and controls, in a simple ($K_c$) form, of the following factors in the ET process:
   i. the influence of stage of growth of vegetation;
   ii. the influence of planting date, crop season length, or cultivar type;
   iii. the influence of plant density, row spacing and canopy architecture;
   iv. the influence of wetting frequency and its contribution to total ET;
   v. the influence of soil water shortage and associated water stress;
   vi. the influence of salinity or other abiotic stresses.

   All of these influences can be integrated into a single $K_c$ curve or set of curves and multiplicative adjustors, using a variety of observational or computational methods.
b. Assisting the transfer of observation and research in ET and water consumption rates across regions and climates by normalizing ET data into the $K_c$ curve.
c. Assisting the development of universal computer models for water management and planning that can be applied with a minimum of local information, for example, observation of planting or green-up dates and lengths of growing seasons.

The $K_c$–$ET_{ref}$ method has been considered by some as being too simple. However, the widespread usage of the $K_c$–$ET_{ref}$ method suggests that most users appreciate and need this level of simplicity, provided, of course, that the simplicity does not induce large reductions in accuracy. The simplicity of the $K_c$ 'curve', where a single, continuous time-series of relative ET rate is represented, may suggest a lack of consideration of the relatively complex processes associated with leaf conductance, aerodynamics, canopy architecture, leaf area and shading, average soil surface wetness, and plant growth. Typically, however, the $K_c$ method, particularly the dual $K_c$ approach, tends to integrate these influences into the $K_c$ value, successfully producing relatively consistent applications of the $K_c$ curve to new areas, time periods and weather conditions. As suggested in the list of influences above, the simple presentation of relative ET by the $K_c$ curve is useful in helping users and even the public visualize the ET process and factors involved.

The consistency of the $K_c$ curve is assisted by consistency in ET rates across a somewhat broad range of vegetation and soil architectures, due to common values of leaf conductance, local mixing of the near surface boundary layer between soil and plant surfaces, and the micro-scale transfer of thermal and radiant energy between soil and canopy. This local-scale mixing, along with the law of conservation of energy associated with the $ET_{ref}$ and upper bounds placed on the $K_c$, tend toward consistency in the $K_c$ from application to application. A theoretical explanation for this behavior of the crop coefficients was discussed by Pereira et al. (1999) relative to aerodynamic and canopy resistances of the crop and the reference crop basing upon former developments by Perrier et al. (1980), Katerji and Perrier (1983) and Peterschmitt and Perrier (1991).

The PM equation can be applied directly to estimate ET by parameterizing it for specific vegetation and soil conditions as suggested by several authors (e.g., Shuttleworth and Wallace, 2009) and discussed by Farahani et al. (2007). This is frequently done for applications in hydrology and can work well for vegetation that nearly or completely covers the ground so that the parameterization is simplified. Alves et al. (1998) and Alves and Pereira (2000) suggested simplified approaches to parameterize complete cover crops and estimating the crop bulk surface resistance from climatic factors instead of the common physiological approach when adopting the PM equation in one step. However, a large challenge in the direct application is establishing characterizations for sparse or multi-layered vegetation such as for forests in semi-arid regions (Stewart, 1983; Denmead, 1984), especially for wet and drying soil surfaces. In these situations, mean heights and locations of sinks for momentum and radiation may be different from mean heights and

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locations of sources of evaporation and sensible heat fluxes. Other challenges with directly application of the PM and other resistance-based equations include difficulties in accurately and consistently quantifying bulk surface resistance for complex canopies, especially when soil water is limiting, and the need for parallel modeling of evaporation from exposed soil that is impacted by frequency and amounts of wetting events and amount of vegetation cover. A recent analysis of related difficulties for forests, where the PM approach is often applied, was reported by Maurer et al. (2013). The traditional PM formulation works best under well-watered conditions of nearly full vegetation cover. It is under these conditions that surface temperature, $T_s$, is closest to air temperature, $T_a$, so that the assumptions explicit in $\Delta$ and emitted long wave radiation, that commonly assume that $T_s = T_a$, and that may neglect buoyancy corrections, are not large. These issues and requirements also affect the $K_c$–$\mathrm{ET_{ref}}$ method; however, that method has more consistent and standardized procedures that provide general compensation for various interactions and feedbacks between vegetation, soil and the near surface boundary layer, which is particularly important for operational purposes comparatively to research.

## 4. Future uses of the crop coefficient and reference and method of FAO56

The FAO56 style of $K_c$–$\mathrm{ET_{ref}}$ approach, that built heavily on FAO24 (Doorenbos and Pruitt, 1977), has been incorporated into a variety of computer models and software used in irrigation scheduling, irrigation systems design, water resources planning, where demands for water are required, and hydrologic modeling, where consumption of water by vegetation and crops is needed. The relatively good consistency and dependability of $K_c$ curves that have been developed over a large number of crop types, and the relatively good accuracy and dependability of ET estimates stemming from the $K_c$–$\mathrm{ET_{ref}}$ method when compared against accuracy of many measurements of ET, lead to the assumption that the $K_c$–$\mathrm{ET_{ref}}$ method is likely to remain in wide usage over the next 15 years and perhaps even longer. $K_c$–$\mathrm{ET_{ref}}$ based applications will continue to be used until more modern and complicated models become widely accepted and are well-tested, robust and easily parameterized. The $K_c$ method may remain in use, if only as a comparison base for new types of models and ET estimation methods.

### 4.1. Continued expansion of the $K_c$ database

Future applications of $K_c$ will expand on $K_c$ for new types and varieties of crops or natural vegetation for which $K_c$ values are not yet published or fully tested. Future $K_c$ estimates are recommended to be based on qualified, well-operated measuring systems or, when those systems are absent, can be based on visual descriptions of plant architecture, including plant spacing and plant height, plant density, plant leaf density and amount, and relative stomatal conductance and how these parameters change or develop over time. Chapters 9 and 10 of FAO56 represented initial attempts at formulating a consistent estimation approach for estimating $K_c$ and $K_{cb}$ from physical observations, which was further developed by Allen and Pereira (2009). That approach, which is largely based on the fraction of ground covered or shaded by vegetation ($f_c$), can be populated in using remotely-sensed estimates of $f_c$ or other vegetation index as discussed in Section 3.6.

$K_c$ determination using ET measured by lysimeter, eddy covariance, Bowen ratio and soil water balance should be continued as primary data collection systems. Remote sensing is expected to play an increased role in actual $K_c$ estimation as previously described. The physical measuring systems serve as important learning devices, since these systems employ physical principles and are set in the real context of growing vegetation. Users of the equipment are 'forced' to observe how vegetation evolves and controls evaporation and transpiration. Users are also 'forced' to learn to deal with the various challenges associated with electronic equipment and sensing and are exposed to the associated physics of radiation, aerodynamics, energy balance and measurement theory in real terms.

### 4.2. Transformations on the crop coefficient curve

FAO24 and FAO56 described $K_c$ curve construction and application in terms of time, for simplicity in application and for training of new users. Typically the $K_c$ curve is divided into four time stages of initial, development, mid-season and late-season. Typical values for growth stage lengths were published with the FAO reports (Allen et al., 1998). Future applications of $K_c$ will and should rely on more sophisticated, dynamic and correct estimates for crop stage lengths, such as introduced in the FAO66. These estimates will include the use of thermal-time units such as growing-degree days to establish lengths of periods, especially for determinate types of crops, the use of moving averages of daily air temperature to estimate planting or greenup dates, and the use of daily air temperature to estimate freezing impacts on delaying beginning or accelerating or terminating the ends of growing periods. These methods are important for improving the translocation of $K_c$ curves to new areas and for assessing the impacts of climate change on future crop water use. Users need to exercise caution in these automated methods for establishing phenological time bases, however, because farmers and producers may or may not adhere to thermally-directed time windows for production, because of other nonclimatic factors influencing planting and harvest dates such as market prices and demands, water availability, impacts of growing period on production quality, and changes in cultivars. Some examples of using thermally-based units to estimate growing periods were described in Section 3.1.

### 4.3. Future advances in calculation of reference ET and evaporation from wet soil

The dual $K_c$ method of FAO56 partitioned the $K_c$ into the basal $K_{cb}$, representing primarily the transpiration component, and $K_e$, representing primarily the evaporation from soil exposed to solar radiation. FAO56 and Allen et al. (2005a,b) described rudimentary adjustments to the estimation of the $K_e$ component to account for effects of surface mulching on reducing evaporation rates and to estimate $K_e$ from surface drip irrigation. These adjustments can be improved using comparisons with measurements from a variety of mulched conditions and times of the year and enhancements to account for a broad range of mulching types and conditions.

Review of recent literature on $K_c$ and crop ET indicates an increasing trend in use of the dual $K_c$ method over the single $K_c$ method. Applications of the FAO56 style $K_c$–$\mathrm{ET_{ref}}$ methodology will, over the next fifteen or so years, be increasingly applied with gridded weather data to produce 'surfaces' of crop ET. Application of the calculation procedures will be housed in geographical information systems and will be scripted in modern languages, such as Python and Java-script, to handle large amounts of weather, soil and crop data. Many applications will be 'packaged' to minimize data requirements and understanding of internal computations by users. This packaging will facilitate the application of spatial computation, but, at the same time, will reduce the required knowledge level of the user. The latter has both advantages and disadvantages. More and more applications will use inverse-modeling and observed ET and vegetation development to develop calibrations for $K_c$ and other parameters. This will sometimes be done with little

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human intervention. However, independent, external review and perhaps intervention will always be needed.

The FAO56 dual $K_c$ procedure requires daily precipitation and reference ET inputs, which, until recently, were solely based on weather variables collected from weather stations. As previously described, since about 2000, $K_c$ and $ET_{ref}$ systems have been increasingly applied using large gridded weather bases including the European Centre for Medium-Range Weather Forecasts (ECMWF), North American Land Data Assimilation System (NLDAS) and Global Land Data Assimilation System (GLDAS). These data sets are produced for the whole globe at 1° spatial resolution or finer and for specific regions at 12 km resolution. Time steps range from hourly to 24-h for calculation of reference ET. The data are produced by relatively complex land process models operated for weather forecasting and climate change modeling. The models are 'forced' using available weather measurements from selected sites around the globe. Results are generally available from NOAA, ECMWF and other web sites.

A second gridded data set is the IWMI World Water and Climate Atlas that includes monthly and annual summaries for weather data on a 10 min arc (one-sixth of a degree) grid. The data include precipitation, air temperature, humidity, hours of sunshine, wind speed, total number of days with and without rainfall, days without frost and PM–$ET_o$. The atlas grid was assembled from 30,000 weather stations around the globe from the period 1961–1990. The Atlas data are intended to support irrigation and agricultural planning.

The employment of gridded precipitation and reference ET data, along with the coding of the $K_{cb}$ and $K_e$ procedures in a geographical information system platform, can produce gridded surfaces of daily $K_e$ and total $K_c$ that incorporate the spatial variation of precipitation and weather. However, prior to calculating $ET_{ref}$ from the GLDAS, ECMWF, NLDAS and other data sets, the air temperature and humidity data should be reviewed to determine whether these data contain 'artifacts' of dryness caused by the assimilation of original weather data that were collected from dry weather sites. These artifacts may produce weather data that are characteristic of regional weather systems, which in semiarid and arid climates reflect general aridity of the region, but may not exhibit the conditioning effects of irrigation where air temperature is reduced and humidity content is increased by ET supplied by irrigation. Generally, the models creating the gridded data sets do not currently include irrigation in the daily soil water balances used to partition available energy into H and ET. The user can review daily maximum relative humidity or dew point and daily minimum air temperature data in the gridded data sets following recommendations by FAO56 and ASCE-EWRI (2005) to assess general aridity of the data sets. Abatzoglou (2011) created a refined 4 km grid of NLDAS data for North America using the PRISM data set that also tends to reduce the arid characteristics of the NLDAS data. Those data produce estimates of $ET_{ref}$ that are more similar to those expected in irrigated settings.

## 5. Summary and conclusions

The crop coefficient - reference ET method is a robust method that provides for straightforward, visually-based derivation and application of the $K_c$ curves over a wide range of climates and locations. The dual $K_c$ method of FAO56 enables the estimation of impacts of surface wetting by precipitation and irrigation on evaporation from soil and the total ET rate, especially during vegetation development and also during periods of dormant vegetation growth such as during winter in extreme latitudes.

Although simple in design and construction, the $K_c$ method successfully incorporates a number of consistent and compensating factors that distinguish the ET of any unique crop from that of the reference ET. This characteristic has attracted a broad range and large number of users, whose backgrounds range from non-scientific commercial and operations-oriented users to relatively sophisticated research users who require high accuracy in estimates.

The FAO56 publication advanced the estimation of evaporation from bare and mulched soil, estimation of $K_c$ and $K_{cb}$ from fraction of ground covered by vegetation, simplified estimation of reduction of ET from salinity. The publication also advocated a unified and standardized estimation of reference ET via the Penman–Monteith method and the QAQC of weather data.

An area of future application of ET computation is in the upscaling to basin, country or even larger areas, where uncertainty is compounded by the spatial scale; GIS becomes a useful tool in handling spatial data, but users need to understand the spatial and temporal complexities required for the upscaling. Finally, another domain of the future, which can support upscaling but also downscaling to the field, is remote sensing of ET via thermally-based surface energy balance (Allen et al., 2007b,c). As discussed before, this area has shown substantial progress in development and application, but still benefits from more development and more knowledge to become effectively operational and to overcome various known problems.

In conclusion, it is anticipated that the use of the crop coefficient curve and reference ET will 'live on' into the future, if, for no other purpose, to serve as a quality assurance/quality control mechanism on observed and simulated data. Deviation from upper limits on $K_c$ and expected shape of the $K_c$ curve over time should give cause to explore data sets more extensively (Allen et al., 2011a). The $K_c$ curve will also continue to serve as a didactic tool to teach policy makers, agricultural producers and students about the realities, trends, behaviors and constraints of water consumption.

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