Evapotranspiration: Progress in Measurement and Modeling in Agriculture

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Abstract. *This article provides a focused survey of progress in crop evapotranspiration (ET) measurement and modeling, with particular emphasis on the aspects of interest to the irrigation profession. The significant advances in understanding and quantifying crop ET during the past few decades are largely due to our increased ability to measure near-surface climate variables and surface energy and momentum exchanges, complemented by progress in soil and plant sensor technology. However, ET measurement is not commonly practiced, and modeling is mostly preferred. Much theoretical progress in ET modeling originated with the 1948 work of Penman and the subsequent modification to the Penman-Monteith (P-M) equation and to multi-layer and sparse canopy models. These advances strengthened confidence in using the combination equation and encouraged a significant step forward through the adaptation of the P-M equation to provide a standard estimate of reference crop ET for use in the long-established, two-step, crop coefficient (K_c) methodology. Recently, there has been a continued progress in this field via the one-step application of the P-M equation to estimate crop ET directly using effective stomatal resistance rather than K_c. This article concludes by drawing attention to a general need to improve crop water productivity by reducing non-beneficial soil evaporation and, in this context, the potential value of using improved methods and models to partition ET and to aid scheduling limited irrigation.*

Keywords. *Bowen ratio, Crop coefficient, Eddy correlation, Evaporation, Evapotranspiration, Lysimetry, Penman-Monteith, Remote sensing, Transpiration, Water productivity.*

This article highlights developments and trends in evapotranspiration (ET) measurement and modeling. As the water resources available for agriculture become limited due to population growth, competition from other users, drought, and quality degradation, the importance of ET as a major component of water use in agriculture grows. The study of ET, the sum of evaporation (E) from the soil and transpiration (T), i.e., evaporation of water through plant stomata, has been popular, resulting in great progress and many publications, some dating back centuries. In such a rich and active field, where should this review start and what should it cover? In the present context, arguably, a century-long synthesis is most appropriate. However, because space is limited, the scope of this review is necessarily more focused on ET research and applications of interest to the profession. Past ET symposia (ASAE, 1966, 1985, 1996) provide a useful backdrop, and we start by elaborating on where ET concepts were when these symposia took place. We then emphasize the progress made since then and draw attention to areas where more work is needed. For broader scope and insight, refer to Jensen (1973), Brutsaert (1982), Hoffman et al. (1990), and Jensen et al. (1990), as well as to Shuttleworth (1993, 2007).

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Overview of Past Progress in Evapotranspiration

Early perceptions of ET were that surface-atmosphere exchange was a simple physical phenomenon little influenced by any overlying vegetation cover. This promoted empirical relationships between the then-limited surface and atmospheric data available and the hypothetical "potential" rate of E, or ET. Some equations were based on temperature alone (Thornthwaite, 1948; Blaney and Criddle, 1950) or pan evaporation (Christiansen, 1968) or radiation and temperature (Jensen and Haise, 1963; Hargreaves and Samani, 1985), and some of these equations are still in general use, albeit with modifications to fit different environments and data. In this mix, the equation of Penman (1948, 1963) was undoubtedly a benchmark. Penman's contribution was pure physics. He derived a "combination equation" by combining two terms, one of which accounted for the energy required to maintain evaporation, an "available energy" term, and the second for the atmosphere's ability to remove water vapor, an "aerodynamic" or "sink" term. However, to facilitate application, Penman introduced empiricism in his wind function and estimated net radiation from sunshine hours. A well-recognized simplification of Penman's equation was later introduced by Priestley and Taylor (1972) for humid environments, in which the aerodynamic term was set equal to a fixed fraction (0.26) of the energy term. The significance of Penman's basic concept gained momentum in the 1960s when Monteith (1965) extended it to plant communities by explicitly recognizing the dependence of transpiration on canopy controls. Rearranging Monteith's original equation results in the formulation that has become known as the Penman-Monteith (P-M) ET equation, written as:

$$ET = \frac{\Delta(R_n - G) + \rho c_p (VPD) / r_a}{\Delta + \gamma(1 + r_s / r_a)} \quad (1)$$

where R_n and G are the net radiation and soil heat flux (W m^{-2}), respectively; Δ is the rate of change of saturated vapor pressure at air temperature (kPa °C^{-1}); ρ is the density of air (kg m^{-3}); c_p is the specific heat of moist air (J kg^{-1} °C^{-1}); γ is the psychrometric constant (kPa °C^{-1}); VPD is the vapor pressure deficit (kPa) measured at a reference level; r_s is the canopy surface resistance to vapor transfer (s m^{-1}), and r_a is the aerodynamic resistance (s m^{-1}) between the crop and the reference height where measurements of the meteorological variables are made. Because experimental and/or theoretical formulations of r_s were not available for all stages of crop growth and all climate conditions, interest at that time remained mostly limited to using equation 1 backwards to investigate the value of r_s from measurements of ET.

By the mid-1960s and early 1970s, many facets of ET measurement and theory emerged, including the energy budget and aerodynamic transfer, but aspects of turbulence theory, advection, plant feedback mechanisms, and eddy correlation measurement remained challenging. By then, the classic circular lysimeters at the University of California, Davis, were operational, measuring ET and exploring above-canopy energy and mass transfers (Pruitt and Lourence, 1985). Difficulties in applying combination formulas and the established popularity of the potential (or reference) ET concept led researchers towards an alternate two-step approach to estimating crop ET (ET_c). In the first step, the rate of ET was estimated for a reference crop (ET_o). This rate was then multiplied by a crop-specific coefficient with the objective of estimating ET_c for different crops relative to this reference rate. The ratio of ET_c to the ET_o for a reference crop (short grass or alfalfa), called the crop coefficient, K_c (Jensen, 1968), was then experimentally determined by growth stage for many crops as the basis for this now long-established two-step approach for estimating crop water use. The use of ET_o (estimated using local climate data) and associated crop coefficients, K_c, became an accepted way to estimate ET_c for well-watered crops, and the K_c methodology was adopted by the UN's Food and Agriculture Organization (FAO) in the 1970s (Doorenbos and Pruitt, 1977). Its subsequent worldwide promotion was a significant step forward in irrigation engineering and water management. With care, using an appropriate model for ET_o and reliable K_c, the two-step approach arguably produces estimates of ET_c within the accuracy of most field-irrigation systems to deliver water (Jensen et al., 1990). This prompts the question, "How precisely does ET_c need to be, since irrigation application (depth or volume) and inherently field soil and crop variability can be much greater than ET_c errors?"

In the 1970s and early 80s, there were rapid advances in electronics and sensor technology. By then, most current measurement methods and instrumentation were available, including improved evaporation pans, lysimeters, net radiometers, and neutron scattering. Rather than using a single value for K_c per growth stage, multiple factors were used to better account for soil evaporation and crop water stress (Wright, 1979, 1981). Studies had largely substantiated the validity of using the simplifying big-leaf assumption (Shuttleworth, 1976) in the P-M equation. This supported the use of bulk values of r_a and r_s to represent the canopy as a whole. However, as pointed out by Itier and Brunet (1996), "The price to pay for this simplicity is to find good expressions for these bulk resistances, which is not a trivial task." Later, in the 1980s and 1990s, there was further rapid progress in data acquisition, remote data access, automation, and in eddy correlation and other measurement techniques. With these advances, short-term (within day) investigations of ET blossomed, but Saxton and Howell (1985) wondered whether many of these were "more progress in doing than thinking, and more methods than theories." Progress was also made in building compartment models describing sparse canopies that allowed partitioning of ET (e.g., Shuttleworth and Wallace, 1985). Transfer of technology made available daily values of reference ET (Heermann, 1985), facilitating early computer applications for irrigation scheduling (Martin et al., 1990). Of particular significance, the superior realism and value of combination equations was recognized, and the P-M equation was adapted to estimate ET_o in the K_c approach (Allen et al., 1994).

Towards the end of the century, the expert consensus was that advanced techniques for measuring crop ET were still used more in research than application (Howell, 1996), and transfer of theoretical models into irrigation practice remained slow (Pereira et al., 1996). Greater reliance on theory was emphasized, including advocating the direct (i.e., one-step) application of the P-M equation to estimate crop water requirements (Shuttleworth, 1993). Later in this article, we return to describe improvements in the K_c methodology together with recent theoretical progress towards one-step estimates of crop water use, but first we summarize other recent advances.

Recent Progress and Trends in ET Measurement and Modeling

Measurements of ET are essential to validate models and valuable for irrigation scheduling and water management, but measurement of ET is difficult and costly, and modeling is mostly preferred. Evapotranspiration can be measured directly using weighing lysimeters or the eddy correlation technique, or indirectly from changes in soil water or via the surface energy budget, using the conservation of mass and energy, respectively. The past few decades have brought advances, largely due to an increased ability to measure near-surface climate variables and surface energy exchange. The rapid developments over the last three decades in instrumentation, data acquisition and remote data access, computer control and automation, and the off-the-shelf availability of measurement tools have enhanced the reliability and affordability of data for use in ET research and practice.

The most significant recent progress results from the ability to measure such near-surface meteorological variables as temperature (of air and soil), humidity, solar radiation, wind (speed and direction), and precipitation routinely using automated climate stations (Snyder et al., 1996). This has greatly facilitated the use of models of ET. Calculation of reference ET was a major task in the 1960s when climate data were measured manually at most once a day using simple instruments and stored in paper records, but its calculation is now routine. Networks of automated climate stations in the U.S. and elsewhere offer a wealth of online data for research and practice, including hourly data that can improve ET_o estimates by better accounting for diurnal variations in microclimate (Irmak et al., 2005; Gavilan et al., 2007). Example networks in the U.S. are CIMIS in California (Snyder, 1983), HPRCC-AWDN in Nebraska (Hubbard et al., 1983), Mesonet in Oklahoma (Brock et al., 1995), CoAgMet in Colorado (Duke, 1996), the Texas North Plains ET Network (Marek et al., 1996), and AZMET in Arizona (Brown, 1998). Some networks offer advanced features such as soil moisture monitoring, 5 minute data availability, and dual-level air temperature and wind speed monitoring (e.g., Mesonet) that have aided large-scale surface flux analysis (Brotzge and Crawford, 2000). There is now greater emphasis on climate data quality (e.g., Meek and Hatfield, 1994; Allen, 1996; Shafer et al., 2000; Feng et al., 2004), including efforts by ASAE to standardize sensor specifications and placement (e.g., Ley et al., 1994; ASAE, 2004). Recently, these were enhanced by standardizing the definition and computation of ET_o (ASCE-EWRI, 2005) and defining detailed but easily invoked procedures for quality controlling the weather data required to calculate ET_o for grass and alfalfa, together with a common basis for determining or transferring K_c curves. Continuing effort is needed to further encourage the wider use of now readily available climate data by consultants and practitioners.

The contribution of complementary advances in plant sensor technology should also be acknowledged (e.g., Kirkham, 2005). Nowadays, once-per-day measurements of pre-dawn leaf water potential, mid-day stomatal resistance, or canopy-air temperature difference are well recognized indicators of crop water stress that can be used to trigger irrigation (e.g., refer to the overview in Phene et al., 1990). The availability of precise, hand-held infrared thermometers allows rapid monitoring of canopy temperature to identify crop water stress (e.g., Ehrler, 1973; Jackson, 1982; Farahani, 1987; Farahani et al., 1993; Colaizzi et al., 2003; Peters and Evett, 2007) for irrigation timing and automatic scheduling (Slack et al., 1981, 1990; Stegman and Soderlund, 1992; Irmak et al., 2000). Sap flow heat gauges can now be used to measure transpiration. This technique has been useful in plant-scale research studies of differential sap flow in plant parts; however, to capture spatial representation, many gauges are needed on many plants. When combined with micrometeorological flux measurements, sap flux techniques are useful for partitioning ET (Hutley et al., 2001), but scaling transpiration sap flux estimates to the footprint of the area-average fluxes measured by, say, eddy correlation systems presents unique challenges (Schaeffer et al., 2000; Williams et al., 2004). Recently, there has been interest in the use of stable isotopes to estimate and partition ET. This technique, introduced into hydrology in the 1960s, now complements conventional flux measurements by identifying the E and T contributions to ET (e.g., Wang and Yakir, 2000; Yepez et al., 2003). It was recently applied to semi-arid grassland (Ferretti et al., 2003) and compared to sap flow and eddy correlation measurements in an irrigated olive orchard (Williams et al., 2004).

Over the last two decades, there has been significant interest in and progress towards deducing area-average values of surface fluxes for large areas. Large-scale flux measurement methods include airborne eddy correlation (Shuttleworth, 1991; Mahrt et al., 2001; Savige et al., 2005), ground and airborne lidar (light detection and ranging) (e.g., Eichinger and Cooper, 2007), scintillometry (e.g., de Bruin et al., 1995), and thermography using remotely sensed radiometric surface temperature measurements. Lidar measurements of the water vapor content directly above corn and soybean canopies revealed a high degree of spatial variability in ET possibly associated with variations in soil type and crop cover (Eichinger et al., 2006). Lidar has particular utility in heterogeneous environments because it provides an integrated value of ET from a surface. Its main drawbacks are very high equipment cost and the need for an independent ET measurement to assess accuracy. Optical methods based on the analysis of atmospheric scintillation offer the ability to integrate surface fluxes of heat and vapor along a path ranging up to a few kilometers (e.g., refer to the review in Hill, 1992). Large-aperture scintillometers (LAS) are now an interesting alternative (Kohsiek et al., 2002) to micrometeorological methods such as eddy correlation, which provide more local flux values at the scale of hundreds of meters. Remote sensing data from ground, aerial, and satellite platforms are now used to derive surface temperature and reflectance and vegetation indices, which can be combined with near-surface meteorological data in energy budget models to calculate heat and vapor fluxes (e.g., Norman et al., 1995; Bastiaanssen et al., 1998; Gieske, 2003). This capability provides opportunity for routinely mapping ET across large areas, such as an irrigation district (Savige et al., 2005) or a basin (Kite and Droogers, 2000; Mo et al., 2004), and may soon allow the routine web presentation of regional maps of reference and crop ET for spatial analysis, management, and planning. Gowda et al. (2007) describe recent, noteworthy studies using airborne and satellite imagery at regional scale.

ET Measurement

Soil Water Budget

Evapotranspiration can be measured by monitoring the change in soil water over a given depth over a specified period in conjunction with measurements or estimates of other components of the water budget (i.e., precipitation, irrigation, deep percolation or upward flow, runoff or run-on, and lateral subsurface flow). Soil sampling and gravimetric analysis of water content is nearly a century old in the U.S., but new and advanced soil water measuring devices such as resistance blocks, tensiometers, neutron probes, TDR, and capacitance sensors have replaced profile sampling (Phene et al., 1990; Evett et al., 1993; Evett and Parkin, 2005). A major source of error in the mass balance method is deep percolation because it is difficult to quantify, especially when the measured depth is less than the wetting front (e.g., Wright, 1990). Extraction by deep roots and soil disturbance during sensor placement are also sources of uncertainty, in addition to the fact that water budget measurement are usually representative of a small area. Capillary rise, fluctuating water tables, and subsurface drainage present even greater challenges with this method (Ayars and Soppe, 2002; Nachabe et al., 2005). In addition, the spatial non-uniformity of rooted crops, e.g., orchards, also poses a challenge when defining a representative depth for sensor placement (Choi and Jacobs, 2007). Nonetheless, this method is among the most common used by irrigation advisors. Because changes in water content over a single day are small and the precision of soil water sensors is limited, the soil water budget method is most appropriately applied over several days (Carrijo and Cuenca, 1992), while 15 minute measurement periods are possible with precision lysimetry.

The combination of advances in electronics and success of TDR technology have led to the availability of many new and relatively inexpensive soil water sensors. Several of these are based on soil dielectric properties and can be described as "TDR like" (Seyfried, 2004). Automated sensors are becoming more common and are particular import in the context of wireless sensor networks, which offer a promising technology for remote monitoring of soil and in-canopy microclimate with high spatial and temporal resolution across farms or irrigation districts. However, the network cost and energy consumption of the sensors are of concern (e.g., refer to the evaluation by Bogena et al., 2007). At present, neutron probes are the most accurate soil water sensing method, while capacitance sensors are less consistent and show sensitivity to the electrical conductivity and temperature of irrigated soils, even when using soil-specific calibrations (Evett, 2007). Evett (2007) found no soil sensor to be practical for on-farm irrigation scheduling, with the possible exception of tensiometers and granular matrix resistance sensors, because they are either too inaccurate (e.g., capacitance sensors) or too costly and difficult to use (TDR and neutron probes). Research and development in pursuit of new and better, but inexpensive, sensor systems is certainly needed.

Surface Energy Budget

Crop ET can be estimated as the residual term in the energy budget equation (Tanner, 1960) that includes net radiation (R_n), soil heat (G), and sensible heat (H) fluxes, applied to a field or to a pixel in a satellite image. Net radiation can be measured using a (relatively costly) four-component system to obtain short-wave and long-wave radiation balance, or using net radiometers (Brotzge and Duchon, 2000), although these are prone to systematic bias. In practice, R_n is most commonly estimated from solar radiation with the aid of temperature data (Jensen et al., 1990). Soil heat flux can be measured using soil heat flux plates (Fuchs, 1986) but is commonly either estimated, e.g., from R_n (ASCE-EWRI, 2005; Payero et al., 2005), or assumed negligible in daily calculations. Neither R_n nor G is currently routinely available from automated climate station networks, and their estimation is therefore a potential source of uncertainty in ET estimates (Batchelor, 1984). Sensible heat flux can be determined using standard meteorological observations in profile methods or estimated instantaneously from radiometric surface temperature measurements. The Bowen ratio-energy budget method is widely employed to estimate ET from measured height differences in temperature and humidity, along with measurements of R_n and G. This method is simple and is still used as a standard against which to evaluate alternative ET measurements or model estimates (Farahani and Bausch, 1995; Payero et al., 2003), but it is problematic when temperature and humidity gradients are too low (Tyler et al., 1997). The problems associated with different humidity sensor offset errors are now resolved: most Bowen ratio systems use pumps to alternatively route the sampled air from different heights to a common humidity sensor (Bausch and Bernard, 1992; Cellier and Olioso, 1993), but the need for frequent maintenance still limits use of this method at remote sites.

Using remotely sensed measurements of surface temperature to estimate H (and consequently ET from the energy budget) has advanced significantly since the 1970s (Brown, 1974; Heilman and Kanemasu, 1976), with studies now made at regional scales (Nieuwenhaus et al., 1985; Hall et al., 1992; Moran et al., 1994; Boegh et al., 2002). A common approach is to estimate H from the canopy-air temperature differences (T_c - T_a) in the formula $H = -c_p\ (T_c - T_a)/r_a$, where r_a is the only variable that cannot be measured (but it is easily computed). This method can be implemented to obtain ET more easily than the P-M equation because it does not require specification of surface resistance. Several researchers have successfully used this approach to determine fluxes from field crops (Hatfield et al., 1984; Slack et al., 1986), sparse canopies (Kustas et al., 1989; Shuttleworth and Gurney, 1990; Chehbouni et al., 1996), and in a greenhouse (Takakura et al., 2005). The current challenge is to separate the canopy and soil contributions and to cope with uncertainties in the value of emissivity that lead to discrepancies between estimated and measured ET from crops with partial canopy cover. The method is more relevant to large-scale ET estimation using airborne or satellite thermal scanners than irrigated fields. Another issue is that this method provides instantaneous values of H (and thus ET), and there is a need to scale up to a full day. Notable early investigations of how to do this include that of Jackson et al. (1977), who estimated daily ET from midday measurements of (T_c - T_a). Instantaneous aerial or satellite-based remotely sensed data may also be infrequently available, but daily values of ET are often needed in practice (e.g., Colaizzi et al., 2006).

Lysimetry

Lysimetry has been around in rudimentary form for several hundred years, but major advances in precision lysimetry have been made in the past 50 years (Howell et al., 1991). The contribution of precision weighing lysimetric measurements to advances in understanding of crop water relations and the development of crop coefficient (e.g., Wright, 1982; Pruitt, 1991; Tyagi et al., 2000; Ayars et al., 2003; Lovelli et al., 2004; Williams and Ayars, 2005) is well recognized. Lysimetry is widely accepted as being an unparalleled standard against which to compare and validate other ET methods and models. The importance of lysimetry is now also recognized in water rights engineering, with lysimeters used to provide basic data on crop water use and return flows (Walter et al., 1991). Increased competition for water resources and more frequent droughts have recently renewed interest and investment in precision lysimetry. A good example is the large monolithic lysimeters that have lately been installed in southeast Colorado to obtain ET data for major crops as the basis for determining the water use and stream depletion that affect the South Platte and Arkansas rivers in the context of interstate compacts (StreamLines, 2004). The proceedings of the international symposium on lysimetry studies around the world (ASCE, 1991) and the recent in-depth article by Howell (2004) represent a good starting point for the reader interested in review of past efforts in this area.

Lysimeters can contain monolithic or reconstructed soil and be weighing and non-weighing, with measurements of the soil water balance required to determine ET in non-weighing lysimeters. Weighing lysimeters can determine soil water changes over short periods with high precision (~0.02-0.05 mm water) by weighing the entire lysimeter mass, and may involve a counter balance and load cells or hydraulic scales. Over the past 35 years, the advent of computers and data loggers and advances in instrumentation have simplified continuous automatic weighing and data recording. The most representative lysimeters have monolithic cores in which the soil structure remains unchanged because disturbed soil cores can affect plant growth conditions (Schneider and Howell, 1991). The locations of some large lysimeters were given by Schneider and Howell (1991), with more recent ones now in Arizona (Young et al., 1996), Florida (Jia et al., 2006), China (Yang et al., 2000), and Spain (Gavilan et al., 2007). Agricultural engineers, including those at the USDA-ARS facility at Bushland, Texas, have developed methods to acquire large monolithic cores using hydraulic jacks to reduce costs (Schneider et al., 1988; Marek et al., 2006). Because of the many potential sources of errors in lysimetry, it is important to know when to trust and when to question lysimeter data. Refer to Howell (2004) for an in-depth discussion of many important factors in lysimetry. These include lysimeter shape and area (area-to-volume ratio), monolithic or reconstructed samples, weighing mechanisms (resolution, counter–balancing), soil profile and depth, field location (site and fetch), variations in plant density and distribution, cultural practices and management on and around the lysimeter, soil profile disturbance, interruption of deep percolation and lateral flow, bypass flow along the walls, and heat flux distortions caused by conductive walls. A carefully installed and well-managed lysimeter should be indistinguishable from its surroundings and, as suggested by Howell et al. (1991), "Many problems can be avoided by reviewing lysimeter literature before designing new lysimeters."

Eddy Correlation

In the past few decades, the eddy correlation method has overtaken the Bowen-ratio energy budget as being the preferred micrometeorological technique for ET measurement because it involves minimal theoretical assumptions (Shuttleworth, 1993) and is now affordable and available off-the-shelf. This technique requires precise, fast-response (~10 Hz) sensors of vertical wind speed, temperature, and humidity, and electronic computation of the correlation between vertical air motion and the constituent of interest to deduce the flux (e.g., refer to the review by Kaimal and Finnigan, 1994; Campbell and Norman, 1998). The preferred sensor for wind velocity is the sonic anemometer and, for humidity, the fast response ultraviolet or infrared hygrometer. Recent interest in climate change has stimulated an explosion in the use of eddy correlation to measure surface energy and CO_2 fluxes (e.g., FLUXNET with over 400 towers worldwide). Shuttleworth (2007) recently cautioned against "irrational exuberance" when applying the eddy correlation technique, mainly because of the potential systematic underestimation of surface fluxes, especially at night, a problem that is not as important for evaporation measurement as for CO_2 measurement.

Progress in instrument development has resulted in the adoption of eddy correlation as the method of choice for assessing other methods of turbulent flux measurement. Nonetheless, poor closure of the energy balance is common when making eddy correlation measurements. An average imbalance of 20% across 22 FLUXNET eddy correlation sites was attributed to underestimated (H + ET) and/or overestimated available energy (Wilson et al., 2002). A 10% to 30% underestimation of (H + ET) was reported even over relatively flat homogonous short vegetation (Twine et al., 2000), and the closure error is typically higher over strongly evaporating surfaces such as irrigated crops. Use of the eddy correlation method therefore requires proper recognition of flux correction procedures and of the effects of flow distortion and sensor orientation. The method is arguably best viewed as providing a measurement of area-average Bowen ratio, with concurrent measurements of R_n and G to allow a check on energy balance closure and independent verification of the eddy flux estimates. At present, there is little use of eddy correlation in irrigation and scheduling practice, but its deployment in agricultural research settings is growing, with interest in expanding its use for calibrating and testing simpler models and developing crop coefficients. Recent applications in irrigated environments include Williams et al. (2004), as well as Jia et al. (2006, 2007) for the purpose of developing citrus and grass K_c curves. In some studies, good agreements (10% or better) were reported between eddy correlation and the soil water balance method (Testi et al., 2004) and between eddy correlation and sap flow measurements (Rana et al., 2005) in orchards. However, more work is needed before eddy correlation can be used to provide an unquestioned measurement of surface energy fluxes.

Thus, both lysimetry and eddy correlation are now accepted methods for directly measuring ET, but where should future investments in ET be made? With the cost of most single precision lysimeters exceeding $50,000, the practical and cost-effective alternative of deploying multiple eddy correlation systems across a wider area is perhaps more attractive and should result in a more spatially representative measurement that is less prone to individual equipment malfunction if area-average ET is required. The recent growth in understanding of how micrometeorological measurements of ET are representative of the vegetation canopy over which they are mounted will aid in this (Gash, 1986; Horst and Weil, 1992). The source area of an eddy correlation measurement is generally considered to extend an upwind distance of about 100 times the sensor height above the canopy (Campbell and Norman, 1998), and it therefore provides an integration of spatial variability not feasible using a lysimeter or soil water sensors. However, lysimetry and soil water budget methods remain preferable if local, crop-specific measurements of ET are needed. Because precision lysimeters are difficult and costly to construct and require special care to operate and maintain, their future use is more likely to be in research and other specialized settings.

ET Modeling

In most practical situations where crop ET rates are desired, the available instrumentation or resources are not sufficient to allow use of the ET measurement techniques described above, and models are used instead. There are several models that seek to estimate crop ET from near-surface climate data; see reviews in Brutsaert (1982), Jensen et al. (1990), Hatfield and Fuchs (1990) and Shuttleworth (1993, 2007). For the purpose of this article, discussion is limited to recent developments in the K_c approach and in the use of the combination equations (including compartment models). As described in more detail below, each of these approaches has its merits and demerits, but the most important and reassuring observation is that currently these two approaches are converging. This is mainly because there is a greater call to theory to improve accuracy and the range of applicability of the K_c approach on the one hand, and a greater determination to address the need for a practical means to specify the difficult-to-define surface resistances in the P-M equation on the other. In recent decades, improved measurement and technology have led to increased understanding of the ET process, and this has enhanced the credibility of using combination equations to calculate ET. This, together with the increased availability of climate data, has resulted in the P-M equation now being selected as the preferred method for estimating ET_o in a revised version of the K_c approach (Allen et al., 1998). However, because of a lack of consolidated information on the required aero–dynamic and surface resistances for different crops, the P-M method was adopted only for estimating ET_o, not yet ET_c. Shuttleworth (2006) provided the theoretical framework to facilitate this next step, i.e., implementing a one-step estimation of ET_c for all crops using the P-M equation, as discussed below.

Crop Coefficients

Two definitions of the K_c curve are provided in Allen et al. (1998). The first integrates the relationship between ET_c and ET_o into a time-averaged K_c curve that does not separate E and T in ET. This is commonly referred to as the "single" K_c approach. The second, called the "dual" K_c approach, splits K_c into the algebraic sum of a basal crop coefficient (K_{cb}) and a soil evaporation coefficient (K_e), i.e., $K_c = K_{cb} + K_e$, and is intended to separate the difference between E and T. The K_{cb} is defined as the ratio of ET_c to ET_o when the soil surface is dry with little soil evaporation but when transpiration is occurring at a non-water-limiting rate (Wright, 1982; Allen et al., 1998). For water-limiting conditions (or other field and crop conditions that limit ET), K_{cb} is reduced by a water stress factor (K_s) described, for example, as a function of the soil water depletion below a threshold stress level (Wright, 1981; Allen et al., 1998). Several recent studies have shown that the dual K_c procedure can provide good estimates of daily ET_c for full-irrigated cotton (Hunsaker, 1999), sorghum (Tolk and Howell, 2001), and alfalfa (Hunsaker et al., 2003a). Howell et al. (2004) reported good ET_c estimates using the dual K_c approach for full-irrigated cotton but suggested that more research was needed before using the water stress factor (K_s) for deficit-irrigated and dryland cotton. The dual K_c approach is more relevant for E calculations and more suitable for scheduling with frequent wetting [e.g., refer to the performance comparison of single and dual K_c in Allen et al. (2005)]. The single K_c approach is more popular and less input data-intensive than the dual K_c approach, and it is better suited for irrigation management and basic scheduling with infrequent wetting (ten days or more). The generalized K_c values used in the single K_c approach are suitable in subhumid climates with average daily minimum relative humidity values of about 45% and calm to moderate wind speed averaging 2 m s^{-1}. For other climate conditions, adjustments are recom–mended (Allen et al., 1998).

The practical simplicity of using a K_c approach is undisputable, including global standardization of the procedures that invoke general energy limits on ET rates, and the recent efforts towards decoupling K_c into basal and evaporation components described above. Acceptance of the K_c methodology is, however, compromised by uncertainties in generalized K_c curves that can lead to errors in ET_c (Hunsaker et al., 2003b). Since local development of K_c requires measuring ET_c during the season (a difficult task), most practitioners rely on published values for their crop. This practice may be unwise because of the empirical nature of K_c, which may limit its transferability into locations where the local climate and management factors deviate from the conditions in which the tabulated value was developed. The literature is mixed in this regard, and it is difficult to infer the exact sources of discrepancy (or otherwise) in field applications with certainty. To some extent, discrepancies are caused by the conditions for crop growth being less than the ideal, pristine growing conditions assumed in the generalized K_c (Allen et al., 2005), and to some extent they are caused by the effect of local climate, soil, management, irrigation method, wetting pattern and frequency, and varietal variations.

Towards a One-Step Approach

Shuttleworth (2006) pointed out that, in practice, respected advocates of the K_c approach implicitly accept the theoretical realism of the P-M equation because this is the starting point for recent attempts (e.g., Pereira et al., 1999) to redefine K_c so that K_c-based estimates match P-M estimates. Redefining K_c in this way leads to the proposal (Pereira et al., 1999) that multiple definitions of reference crop ET for groups of crops with similar aerodynamic properties be defined, and new field studies be made to index the ET rate for crops in each group to the most relevant of these different reference crop estimates. Shuttleworth questioned whether this approach is preferable to the alternative approach of making a simple calculation of aerodynamic resistance based on crop height and carrying out field studies to define the effective whole-canopy stomatal (i.e., surface) resistance, r_s, for different crops. However, adopting this alternative one-step use of the P-M equation requires that two outstanding issues be addressed.

The first issue is that the meteorological variables from which crop ET estimates are made are often available at a fixed height (usually 2 m). However, when using the P-M equation, these values are required at some level (the reference level) above the crop for which calculations are to be made, and some crops are taller than 2 m. This issue can be resolved theoretically by specifying a hypothetical blending height (at, say, 50 m) near the interface between the surface layer and the mixed layer in the atmospheric boundary layer (ABL) where meteorological conditions are assumed to be independent of the underlying crop.

Shuttleworth (2006) derived expressions that allow calculation of the aerodynamic resistances to this blending height and the vapor pressure deficit at the blending height from the climate variables measured at 2 m, thus allowing the P-M equation to be used to estimate ET_c from 2 m climate data and crop-specific values of effective stomatal resistance (refer to eq. 28 in Shuttleworth, 2006).

A second issue is that, currently, there are no tables of the effective all-day average values available for the stomatal resistance of different crops equivalent to those that exist for K_c. Shuttleworth (2006) called for field studies to address this need as a simpler alternative to redefining K_c (e.g., Pereira et al., 1999) and using multiple definitions of ET_O as discussed above. However, recognizing the need for an interim source of crop-specific r_s estimates pending results of such field studies, Shuttleworth (2006) also proposed a methodology for translating existing K_c values into equivalent r_s values for different crops. Doing this is complicated because K_c values are not a pure measure of crop characteristics but also depend on the climate prevailing at the time of their development. Using results from modeling studies of the coupled interaction between land surfaces and the ABL as background, and by making additional assumptions, a simple equation for transforming generalized K_c into r_s was derived (refer to eq. 39 in Shuttleworth, 2006). Replacing this r_s in the P-M equation (using 2 m data as described above) provides the one-step P-M equation, referred to as the Matt-Shuttleworth (M-S) equation (refer to eq. 40 in Shuttleworth, 2006). Pending the availability of a table of field-calibrated values of effective all-day average stomatal resistance, the Matt-Shuttleworth ET equation provides an interim opportunity to make a one-step estimate of ET_c from the values of K_c using 2 m climate data.

Challenges: Partial Canopy and Water Stress

In the face of the increasing global concern about water scarcity and sustainability, the importance of the role of ET is perhaps best captured by the UN's slogan "more crop per drop." Alternative slogans are "same crop, less drop," the more ambitious "more crop, less drop," or the more realistic "less crop, lesser drop." These slogans reflect alternate ways of improving water use efficiency, or the now preferred term "water productivity," which is defined as value (i.e., yield or biomass) per unit ET or water used. A major pathway to increase the "crop per drop" in irrigated agriculture is through reducing soil evaporation (e.g., refer to Howell, 2006, for major pathways in irrigated agriculture), the relatively "easy" water to conserve with much less cost to yield. Improving water productivity by reducing evaporation will surely benefit from methods and models that allow partitioning of ET, particularly those capable of describing partial cover under conditions of changing surface soil moisture.

Notwithstanding the above, E and T are rarely measured separately. Notable modeling efforts include the widely used functional soil evaporation model of Ritchie (1972) for incomplete cover, the dual K_c approach (Allen et al., 1998), and the two-source model of Shuttleworth and Wallace (the S-W model; Shuttleworth and Wallace, 1985). The dual K_c approach allows E computation (i.e., K_e coefficient) and is appealing (e.g., Allen, 2000). Procedures to estimate K_e are detailed in Allen et al. (1998) and require a daily soil water budget computation for the top soil in addition to estimates of fraction of wetted surface. This approximation method affords good accuracy when applied carefully and thoughtfully, and it is capable of incorporating impacts of varying soil wetness (i.e., drip vs. flood) and frequency. The S-W model has also been widely applied in agriculture (e.g., Lafleur and Rouse, 1990; Wallace et al., 1990; Farahani and Bausch, 1995) and has recently been extended to inter-cropping systems (e.g., Wallace, 1996) and to residue-covered fields (e.g., Farahani and Ahuja, 1996).

Above we described the one-step application of the P-M equation in the form of the Matt-Shuttleworth equation to estimate water use in fully irrigated crops, with a changing crop height and the (traditional) linear interpolation of K_c if this is required for the crop stage. Because the calculation is made using the P-M equation, it makes proper allowance for the different aerodynamic characteristics of crops in all atmospheric aridity. However, the P-M equation only applies to crops with full cover, and using the P-M equation to improve estimates of ET for crops with partial cover is, strictly speaking, not theoretically correct and has been shown experimentally to underestimate ET during the early season (Lafleur and Rouse, 1990; Farahani and Bausch, 1995). The interim formulation of surface resistance in the one-step model uses K_c, although K_{cb} might have been more appropriate as K_c is an average value that includes soil evaporation. The use of K_c, however, implies an implicit accounting of soil evaporation in the interim one-step approach at all growth stages. We speculate that for well-irrigated crops during early and late season, the ambient leaf area index may provide a basis for an interpolation between the effective resistance of moist soil and the effective stomatal resistance for different well-watered, fully grown crops. However, further development of the two-source S-W model is the preferred approach to a P-M based modeling of ET for canopies with partial cover. The two-source model also better relates to the need for a model capable of giving separate representation of E and T for use in water productivity studies, and for evaluating and calibrating simpler models for use in irrigation practice. An ongoing challenge with the S-W model is how to quantify the soil surface resistance, which so far has most successfully been described as an exponential function of the near-surface soil moisture (e.g., Farahani and Bausch, 1995; Daamen and Simmonds, 1996).

A rapidly growing need is to estimate crop ET under water-limiting conditions, i.e., deficit irrigation. This is of great importance in many dry areas of the world with a shrinking share of agricultural water, including nearly all western U.S. states with current and pressing water allocation and stream depletion issues. The K_c approach with an empirical K_s stress coefficient has been proposed and used (e.g., Doorenbos and Kassam, 1979; Wright, 1982; Allen et al., 1998). The parameter K_s describes the effect of water stress on crop transpiration, and its use requires a daily soil water budget computation for the root zone. Other formulations using climatological resistance weighted by pre-dawn leaf water potential (Rana et al., 1997) or soil water content (Ortega-Farias et al., 2006) have also been used to adjust r_s in P-M type applications. Mechanistic models are needed to better quantify the weighing, i.e., K_s, factors and understand the effect of stress on leaf expansion, stomata closure, and early senescence as these affect growth and transpiration. We suggest more research to allow better understanding of the use of the P-M equation for water-stressed crops.

Most challenging is modeling the yield response to water availability, which requires a capability to model ET for all canopy cover and stress conditions in addition to a capability to model biomass accumulation as affected by abiotic stresses. Predicting yield is becoming increasingly important to optimize irrigation under limited water supplies for enhanced sustainability and profit. Heermann (1985) anticipated this more than twenty years ago:

"Managers will in the future, use yield models to implement management strategies for limited available water. These models will require accurate estimates of ET and some models will require separating evaporation and transpiration" (p. 333).

Past progress in this area is plentiful (e.g., Hanks, 1974; Doorenbos and Kassam, 1979; Taylor et al., 1983), and the resulting understanding is currently being recaptured in the relatively simple and robust FAO model, AquaCrop, which is built on the premise of conservative behavior of biomass water use efficiency (Steduto et al., 2007). Early evaluations of the AquaCrop model under a range of irrigation regimes for cotton (Farahani et al., 2007) and maize (Hsiao et al., 2007; Heng et al., 2007) show promising results in crop ET and yield predictions.

Concluding Comments

Recent progress has been substantial, but the transfer of advances in ET modeling and measurements into irrigation practice remains slow. Irrigation researchers have contributed to and embraced the advances in the science and technology of ET, but many practitioners still operate scheduling using crude procedures, including intuition and experience and the "feel" method. The measurement of ET from irrigated fields is rare, mainly because of the lack of resources at the farm level to apply most of the measurement techniques discussed here. Modeling is preferred, yet there is limited opportunity for the blind application of any model to a field condition without some parameter calibration and verification to ensure on-site behavior. There is a real need for innovative methods that can provide sound and affordable estimates of ET that use "plug-and-play" features to link better with on-farm managerial skills.

This review also draws attention to the substantial progress towards greater reliance on current ET theory and the use of combination equations. The P-M equation has been adapted to estimate reference crop ET, and recent theoretical developments enable continuing progress towards the one-step application of the P-M equation for crop water use estimation based on effective stomatal resistance rather than a crop coefficient. The one-step approach is attractive, but its use warrants careful examination and field testing before it becomes an operational method. Strategies to increase water productivity and sustain available water resources that involve deficit or supplemental irrigation are increasingly advocated, and application of both the simple and advanced models discussed in this article also need significantly more field testing in stressed conditions. In principle, the P-M equation provides a basis to estimate ET in all conditions of crop water stress, but its use in deficit irrigation management requires better quantification of the effect of stress on stomatal control. In fact, this need was recognized decades ago when Monteith (1985) suggested:

"It is time that soil physicists and root physiologists got together with microclimatologists and leaf physiologists to do some comprehensive work on the soil-plant-atmosphere continuum of crops throughout the growing season. A better understanding of how effective stomatal resistance changes with time when water is limiting is needed" (p. 10).

We concur, and we complement our call for renewed investigation of the one-step P-M based approach for estimating ET by also advocating research to better understand and model the effect of water stress on surface resistance.

In the past, the lack of simple and affordable tools to measure ET in the field has been a major shortcoming. The soil water budget approach is currently the most popular field method used to estimate ET, but most of the available sensors used in this approach are considered by experts to be either too inaccurate or too costly and difficult to use, and therefore not practical for on-farm irrigation scheduling. Relevant equipment research needs to continue because, looking forward, this presents the only opportunity for measurement-based irrigation scheduling for individual fields.

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