Estimating Crop Water Use of Cotton in the Texas High Plains
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ABSTRACT
The growth and yield of cotton (Gossypium hirsutum L.) in the semiarid Texas High Plains is driven by the amount of water available to the crop through rainfall and irrigation. Various methods have been developed for quantifying the crop water use (CWU) of agricultural crops. In this study, we described a method for estimating CWU that uses a modified version of the Penman–Monteith Equation. In this method, CWU is equal to the transpiration of a well-watered crop with complete ground cover (determined from ambient environmental conditions) multiplied by the amount of plant canopy present (quantified by crop ground cover) and a parameter ($F_s$) related to the effects of stomatal closure. For irrigated and dryland cotton that are acclimated to their respective environments, $F_s = 1$. This suggests that control of canopy leaf area is a primary mechanism for acclimating to the surrounding environment. When $F_s < 1$, the plant is not acclimated with its environment and must rely on stomatal closure to conserve available water in the root zone. The method was developed using surface energy balance data and remotely sensed crop ground cover for three fields near Lubbock, TX. This method could be used in irrigation scheduling where irrigation is used to replace the daily CWU of a crop. This approach might be superior to the standard crop coefficient approach because it could use remotely sensed crop ground cover as a “spectral crop coefficient” that would make the resulting estimates of CWU specific to individual fields.

In the semiarid Texas High Plains of the United States, the growth and yield of agricultural crops such as cotton is inexorably linked to the amount of water available from precipitation and/or irrigation. Many studies (Sammis, 1981; Hanks and Rasmussen, 1982; Howell et al., 1984; Hay and Walker, 1989) have shown a linear relationship between crop dry mass or yield and the water used by the crop over the growing season. The ability to quantify CWU allows researchers to study the interaction of crops and their environment, and supports practical crop production activities such as irrigation scheduling. While various definitions of CWU exist, we choose to define it as the water used by the crop, which would exclude soil evaporation. Thus, from an agronomic sense, our definition of CWU and transpiration are roughly synonymous. For agricultural fields, measurements made with lysimeters or micrometeorological sensors (such as eddy covariance systems) typically quantify evapotranspiration (ET), the combination of crop transpiration and soil evaporation. However, ET values approach CWU when the soil evaporation component is comparatively small, as when the upper portion of the soil profile is dry or when the crop canopy completely covers the soil surface.

Numerous methods have been developed for estimating the water use of a growing crop. Perhaps the most popular is that described by Monteith (1965), which was developed by introducing aerodynamic and surface resistance terms into the surface energy balance approach of Penman (1948). While this “Penman–Monteith” method applies to evaporation from any uniform, continuous surface, it can be used to estimate crop transpiration by assuming that the evaporating surface is a uniform, continuous plant canopy that completely covers the soil surface (Van Bavel, 1966). This is often called the “Big-Leaf” form of the Penman–Monteith Equation, and can be expressed as follows (Allen et al., 1989),

$$\lambda ET = \frac{\Delta (R_n - G) + \rho_a c_p (e_s - e_v) / r_s}{\Delta + \gamma (1 + r_f / r_s)}$$

where ET is the evapotranspiration rate in kg m$^{-2}$ s$^{-1}$, $R_n$ is the net radiation in MJ m$^{-2}$ s$^{-1}$, $G$ is the soil heat flux in MJ m$^{-2}$ s$^{-1}$, $(e_s - e_v)$ is the vapor pressure deficit of the air in kPa, $\rho_a$ is the air density in kg m$^{-3}$, $c_p$ is the specific heat of air at constant pressure in MJ kg$^{-1}$ °C$^{-1}$, $\Delta$ is the slope of the saturation vapor pressure curve in kPa °C$^{-1}$, $\gamma$ is the psychrometric constant in kPa °C$^{-1}$, $\lambda$ is the latent heat of vaporization in MJ kg$^{-1}$, and $r_f$ and $r_s$ are the surface and aerodynamic resistances, respectively, in s m$^{-1}$. In this approach, proper assignment of the value for $r_s$ allows the calculation of crop transpiration for conditions ranging from optimal to limited water supply (Van Bavel, 1967). When actual measurements of ET are available, as through studies involving lysimeters, it is possible to accurately calculate the surface resistance associated with a given set of growing conditions (Van Bavel, 1967; Hatfield, 1985; Howell et al., 1997). In many situations, however,
the value of $r_c$ may not be known. This difficulty has limited the practical application of the Penman–Monteith method.

It has been observed that the amount of water used by crops per unit ground area is related to the amount of plant canopy present, measured either by leaf area index (LAI) or ground cover (GC). In general, CWU tends to increase with increasing LAI up to a value of approximately 3 m$^2$ m$^{-2}$, which represents full ground cover (GC = 1) for many crops (Chang, 1968; Ritchie, 1972; Bunting and Kassam, 1988). The influence of the canopy has been incorporated into the "crop coefficient" method (Allen et al., 1998) which uses a two-step approach to estimate the water used by a growing crop. In the first step, "reference evapotranspiration" (ET$_0$) is calculated for a hypothetical reference crop (typically a well-watered short grass) using a modified form of the Penman–Monteith equation. Crop evapotranspiration (ET) is then calculated by multiplying the value of ET$_0$ by an empirically determined factor (the "crop coefficient" K$_c$) that is specific to the crop type, crop stage, and agricultural region. The shape of the function representing K$_c$ varies over the growing season in a manner similar to the variation in crop GC. While ET$_c$ calculated using the basic crop coefficient approach includes soil evaporation, a "dual crop coefficient" approach can be used to separate the crop transpiration and soil evaporation components (Allen et al., 1998).

The crop coefficient approach simplifies the estimation of ET$_c$ by assuming a constant value for the surface resistance in the Penman–Monteith equation. It calculates ET$_c$ under "standard conditions" which, according to Allen et al. (1998, p. 90), represent "the upper envelope of crop ET and represents conditions where no limitations are placed on crop growth or ET due to water shortage, crop density, or disease, weed, insect, or salinity pressures." While calculated values of ET$_c$ can be adjusted for nonstandard conditions that might occur in a specific agricultural field (Allen et al., 1998, p. 159), this complicates the procedure by introducing additional factors that must be measured or estimated for the field. Still, the crop coefficient method has found wide application, particularly in irrigation scheduling.

Remote sensing is effective in estimating crop canopy characteristics such as LAI and GC. For this reason, a number of researchers have used remote sensing to evaluate crop coefficients (Heilman et al., 1982; Bausch and Neale, 1987, 1989; Neale et al., 1989; Bausch, 1995; Hunsaker et al., 2003, 2005). In previous studies, the relationships between remote sensing data (usually in the form of a vegetation index, such as NDVI) and the crop coefficient have been determined empirically. Such analyses can lead to relationships that are specific to a site or a set of weather conditions occurring during the study.

Recently, a nonempirical method for calculating crop GC directly from multispectral remote sensing data has been described (Maas and Rajan, 2008; Rajan and Maas, 2009). Since remote sensing can provide observations of the actual state of the crop during the growing season, its use could improve the accuracy of CWU estimates by allowing their evaluation for a range of conditions, including nonstandard conditions. Such an approach may be developed as follows. For a crop with partial ground cover, the surface resistance $r_s$ can be partitioned between the crop canopy resistance $r_c$ and the soil resistance $r_{soil}$ according to the equation (Jordan and Ritchie, 1971),

$$\frac{1}{r_s} = \frac{1}{r_c} + \frac{1}{r_{soil}} (1 - GC)$$  \[2\]

The second term on the right side of this equation is related to the soil evaporation component of ET. Since our definition of CWU involves only the water used by the crop, this term may be ignored. So, in this special case,

$$r_s = r_c / GC$$  \[3\]

From this, we can see that Eq. [1] implicitly contains the effects of GC in the surface resistance term. We would like to develop a method of estimating CWU in which the effects of GC are separated from the effects of the other environmental factors. Hypothetically, this separation can be accomplished by the following simple expression,

$$CWU \approx ET_{fc}(GC)$$  \[4\]

where ET$_{fc}$ represents the ET of a crop with complete ground cover. Since GC = 1, ET$_{fc}$ would represent crop transpiration as a result of Eq. [2]. Basically, this expression states that the CWU is approximately equal to the transpiration of a full crop canopy (determined by the ambient environmental conditions) multiplied by how much crop canopy is present (determined by GC, which ranges from 0 to 1). Ritchie (1972) used a similar concept in estimating crop transpiration, except he used an empirical term involving LAI instead of GC. He noted that this term reached a value of 1 at LAI = 2.7, which corresponds to complete ground cover for many crops. The form of Eq. [4] is reminiscent of the standard crop coefficient approach (Allen, 2003) where, in this case, GC takes the place of the crop coefficient. Since GC can easily be obtained using multispectral remote sensing, we have informally adopted the name “spectral crop coefficient” for GC in Eq. [4].

The ET$_{fc}$ term in Eq. [4] can implicitly contain effects of water stress through the value of $r_c$, which is related to the degree of stomatal closure. It is possible to extract these effects by re-writing the expression as follows,

$$CWU \approx PET_{fc}(GC)(F_s)$$  \[5\]

where PET$_{fc}$ represents the potential ET of a well-watered, unstressed crop with complete ground cover and $F_s$ is a parameter that quantifies the effects of stomatal closure on transpiration. Like GC, the value of $F_s$ ranges from 0 to 1. PET$_{fc}$ can be evaluated from environmental conditions using a modified form of the Penman–Monteith Equation, and multiplied by GC and $F_s$ to provide an estimate of CWU,

$$CWU = PET_{fc}(GC)(F_s) = \left(1 - \frac{\Delta R_{ns}}{\Delta + (1 + r_{soil} / r_{fc})} \right) \left(1 - \frac{\rho \varepsilon (e_c - e_s)}{\Delta + (1 + r_{soil} / r_{fc})} \right)$$  \[6\]

In this expression, the values of $R_{ns,fc}$ and $r_{soil,fc}$ are representative of net radiation and aerodynamic resistance of a crop with complete ground cover, and $G$ has been omitted since it should be small under full canopy conditions. Also, $r_{soil}$ represents the canopy resistance of a well-watered, unstressed crop.

Wanjura et al. (1984) reported values of $r_c$ in the range 50 to 60 s m$^{-1}$ for fully irrigated cotton with 50% GC grown at
Lubbock, TX. Jordan and Ritchie (1971) reported a value for $r_c$ of 130 s m$^{-1}$ for cotton with 30% GC grown at Temple, TX. They noted that their stomatal resistance measurements used to calculate $r_c$ values were approximately 2.5 times greater than those commonly cited for crops with maximally open stomata, which would result in a value for $r_c$ of 52 s m$^{-1}$ for unstressed cotton. Gonzales-Dugo et al. (2006) reported values for $r_c$ of 41, 42, and 16 s m$^{-1}$ for unstressed cotton at Maricopa, AZ, estimated from remotely sensed canopy temperature. Based on the results of numerous field studies, Allen et al. (2006) recommended that a value of 50 s m$^{-1}$ be used for $r_c$ in calculating PET for well-watered vegetation with complete ground cover using the Penman–Monteith method for time periods on the order of an hour. In this case, since GC = 1, $r_c$ would be the same as $r_c$, according to Eq. [2]. From these observations, it appears that the value for $r_c$ in Eq. 6 should be around 50 s m$^{-1}$.

Equation [6] provides a means for estimating CWU based on micrometeorological data (to evaluate PET$_{fc}$), crop GC (which can be obtained using remote sensing), and an estimate of $F_s$. Since $F_s$ is related to the degree of stomatal closure, its value can be thought of as an indicator of the degree to which the crop plants are acclimated to their surrounding environment. Increasing the leaf area of a plant increases its potential for photosynthesis and growth. However, increasing the leaf area also increases transpiration and depletion of soil water. The plant must strike a balance between photosynthesis and transpiration to maximize leaf photosynthesis without exhausting soil water reserves before plant maturity. Since closing stomata reduces photosynthesis, reducing canopy leaf area is a more efficient way to optimize photosynthesis (Glenn et al., 2008). Thus, under water-limiting conditions, it is better for the plants to have less leaf area, with the stomata on these leaves open, than to have more leaf area, with the stomata on some or all of these leaves closed. Plants that have struck this balance within their environment should have a value of $F_s$ = 1.

Rosenthal et al. (1987) showed that, as soil water was depleted by cotton and grain sorghum [Sorghum bicolor (L.) Moench] plants, leaf expansion rate was reduced before leaf transpiration. They also noted that senescence of older leaves in the canopy increased as soil water became limiting. These processes provide mechanisms for plants under water-limiting conditions to develop and maintain a smaller leaf canopy that, through reduced total transpiration, can conserve soil water reserves without resorting to stomatal closure that would reduce photosynthesis. Leaf expansion and senescence are relatively slow processes, and thus cannot completely accommodate rapid changes in environmental conditions. When agronomists in regions with high evaporative demand grow crops initially under well-watered conditions and then terminate the water application, it is common to observe a resulting rapid increase in stomatal closure and decrease in transpiration (e.g., Van Bavel, 1967). In these cases, switching off the water produces an abrupt change in the crop’s environment, one where the rapid decline in soil water cannot be sufficiently slowed by reductions in leaf expansion and/or increases in leaf senescence. As a result, the plants close their stomata to reduce transpiration until leaf expansion and/or senescence can reduce the size of the canopy and bring about a new balance within the changed environment. During this period of re-adjustment, one would expect to find the value of $F_s$ to be <1.

The objective of our study was to evaluate the method of estimating CWU described by Eq. [6] using environmental and remote sensing data collected from cotton fields in the Texas High Plains. Values of crop GC used in the procedure were obtained from routine satellite observations, and results were compared with values of ET obtained from surface energy balance measurements involving eddy covariance systems. Based on these results, we provide an assessment of how well this approach appears to perform under field conditions in this region.

**MATERIALS AND METHODS**

The study was conducted in 2008 and 2009 in three commercial fields located in the Texas High Plains. The study involved analysis of several types of data, including satellite imagery, weather observations, and measurements of ET. Methods of data collection and analysis are described in the following paragraphs.

**Study Site**

The three fields used in this study (hereafter referred to as Field 1, Field 2, and Field 3) are part of the Texas Alliance for Water Conservation (TAWC) Demonstration Project being conducted in the Texas High Plains to promote conservation of regional water resources. Two of the fields were planted to cotton and provided data for estimating CWU, while the third field was bare and provided additional data for interpreting the results. All three fields are rectangular in shape. The study was conducted in Fields 1 and 2 in 2008 and in Field 3 in 2009. Field 1 (14.5 ha) is located approximately 3.25 km southwest of Lockney, TX (34°7’30” N, 101°26’31.2” W). It was planted to cotton and was irrigated using subsurface drip irrigation. The crop rows were oriented north–south. The irrigation was terminated on 8 Sept. 2008 (Day 252). Field 2 (20.6 ha) is located approximately 3.25 km north of Lockney. It was planted to cotton in rows oriented east–west. Field 2 was not irrigated. Fields 1 and 2 were planted on 5 May (Day 126) and 21 May (Day 142), respectively. Field 3 (19.1 ha) is located approximately 6.75 km southwest of Lockney. It had a tilled bare surface during the study in 2009. The soil in all three fields was Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) with 0 to 1% slopes (NRCS, 1978). The climate of the study region is semiarid with an average annual precipitation of 460 mm.

**Remote Sensing Data**

Landsat-5 Thematic Mapper (TM) imagery containing the study site was acquired on 11 dates during the 2008 growing season: 18 May (Day 139), 3 June (Day 155), 19 June (Day 171), 5 July (Day 187), 21 July (Day 203), 6 August (Day 219), 22 August (Day 235), 7 September (Day 251), 23 September (Day 267), 9 October (Day 283), and 25 October (Day 299). Landsat-7 Enhanced Thematic Mapper (ETM+) imagery containing the study site was acquired on five additional dates during 2008: 11 June (Day 163), 27 June (Day 179), 15 September (Day 259), 1 October (Day 275), and 17 October (Day 291). Each image, located according to the Landsat World Reference System (WRS-2) along Path 30 at Row 36, was obtained from the U.S. Geological Survey (USGS) EarthExplorer website (http://edcgsn07.cr.usgs.gov/EarthExplorer/). Pixel size in...
the imagery was specified as 30 m, and systematic correction (LIG) was applied by USGS to the image data. In systematic correction, the image is rotated, aligned, and georeferenced to a user-defined map projection (WGS84), and is radiometrically corrected based on sensor characteristics (Chander and Markham, 2003).

Data extracted from the Landsat imagery were used to estimate GC for Fields 1 and 2 on all image acquisition dates using the procedure described by Maas and Rajan (2008). Image data analysis was performed using ENVI image processing software (ITT, Boulder, CO). A scatterplot of each image (excluding portions containing clouds, cloud shadows, and water bodies) was constructed by plotting pixel digital count (DC) values in Band 4 (NIR spectral band) vs. corresponding DC values in Band 3 (red spectral band). The bare soil line and the point corresponding to 100% GC were then identified by visual inspection of each scatterplot, allowing calculation of the value along the appropriate equation of the bare soil line to calculate the value of PVI corresponding to each field. The GC for each field on each image acquisition date was then calculated by dividing the PVI value corresponding to the field by the appropriate value of PVI corresponding to 100% GC. Values of crop GC for Fields 1 and 2 for days between satellite image acquisition dates were estimated using linear interpolation (Fig. 1).

**Energy Balance Data**

For this study, the steady state surface energy balance (EB) was defined by the equation (Amer and Hatfield, 2004),

\[ R_n - (H + LE + G) = 0 \]  \[7\]

where \( R_n \) is the net radiation, \( H \) is the sensible heat flux, \( LE \) is the latent heat flux, and \( G \) is the soil heat flux. The units of all terms in Eq. \[7\] are W m\(^{-2}\).

Two mobile ET systems operated in conjunction with the TAWC Demonstration Project were used to measure the EB components. One mobile ET system was located at Field 1 during the period from 7 Aug. 2008 (Day 220) through 4 Oct. 2008 (Day 278). The other mobile ET system was located at Field 2 during the period from 31 Aug. 2008 (Day 244) through 3 Oct. 2008 (Day 277). One of the mobile ET systems was located at Field 3 during the period from 24 Mar. 2009 through 9 Apr. 2009. Sensors used in the mobile ET systems are listed in Table 1. A mobile system consisted of a trailer with a mast holding the CSAT-3 sonic anemometer, infrared gas analyzer (IRGA), and temperature/RH probe that comprised the eddy covariance system. These sensors were mounted on the mast according to recommendations provided by Campbell Scientific (2006). The trailer could be backed into the edge of an agricultural field to make measurements when the wind was blowing across the field in the direction of the trailer. The set of sensors mounted on the mast were maintained at a height of 2 m above the top of the plant canopy for Fields 1 and 2, and at a height of 2 m above the bare soil surface for Field 3. The set of sensors used to measure soil heat flux were buried in the field according to recommendations provided by Campbell Scientific (2007). The net radiometer was mounted on a tripod in the field approximately 2 m above the plant canopy for Fields 1 and 2, and approximately 2 m above the bare soil surface for Field 3. Data from all sensors were measured and recorded at a 10 Hz sampling rate using a CR3000 data logger (Campbell Scientific, Logan, UT). The raw high frequency data used in determining \( LE \) and \( H \) were despiked following the methodology of Vickers and Mahrt (1997) and detrended. The wind velocity components were rotated (two dimensional) to align them to the Cartesian frame of reference (Kaimal and Finnigan, 1994). After the data were processed, \( H \) and \( LE \) were calculated according to the procedure described by Baldocchi (2003). Sensible heat fluxes were corrected for buoyancy effects following the methodology of Liu et al. (2001) and \( LE \) fluxes were corrected for density fluctuations (Webb et al., 1980). Thirty-minute average values were calculated for the EB components.

Each mobile ET system was situated along the north edge of the field it was measuring, approximately halfway between the east and west borders of the field, to preclude its interference with field management activities. Data from a mobile ET system were not used in this study if the prevailing wind direction was <110° or more than

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**Table 1. Sensors used in each of the mobile evapotranspiration systems to measure various environmental variables.**

<table>
<thead>
<tr>
<th>Environmental variable</th>
<th>Sensor† (per system)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net radiation</td>
<td>Kipp &amp; Zonen NR-Lite net radiometer (1)</td>
</tr>
<tr>
<td>Water vapor concentration</td>
<td>Li-COR LI-7500 open-path IRGA (1)</td>
</tr>
<tr>
<td>Wind speed and direction</td>
<td>CS CSAT3 3-D sonic anemometer (1)</td>
</tr>
<tr>
<td>Soil heat flux</td>
<td>Hukseflux self-calibrating soil heat flux plate (4)</td>
</tr>
<tr>
<td></td>
<td>CS TCAV averaging soil thermocouple probe (2)</td>
</tr>
<tr>
<td></td>
<td>CS CS616 water content reflectometer (2)</td>
</tr>
<tr>
<td>Air temperature and humidity</td>
<td>Vaisala HMP50 temperature and RH probe (1)</td>
</tr>
</tbody>
</table>

† Mention of manufacturer’s names is for informational purposes only and does not constitute an endorsement by the authors or their organizations.
250° (measured clockwise from north) to exclude situations where the fetch was not dominated by the environment within the field.

Energy balance data were used in the study only for those days when the fetch requirements were met and soil surface was dry. For Fields 1 and 2, the requirement of a dry soil surface was intended to minimize the soil evaporation component of measured ET. During the experiment period, these requirements were met for a total of 23, 8, and 10 d for Fields 1, 2, and 3, respectively. To investigate possible changes in the nature of ET associated with termination of the irrigation in Field 1, the entire data set for that field was partitioned into three periods (see Fig. 1): Period 1, which included data before termination of the irrigation; Period 2, which included data from days shortly after termination of the irrigation when GC was beginning to decrease; and Period 3, which included data from days following the termination of irrigation when GC was decreasing rapidly. Daytime EB closure was evaluated for all three study fields. Thirty-minute average values of $R_a$ were regressed against the sum of corresponding values of $LE$, $H$, and $G$ (Meyers and Hollinger, 2004) using the reduced major axis (RMA) regression method (Sokal and Rohlf, 1981; Wilson et al., 2002). The RMA method was used instead of standard least squares regression to better account for the random errors associated with the measurements of the independent variable (Wilson et al., 2002).

**Flux Footprint Analysis**

A flux footprint analysis was conducted to determine the degree to which different parts of the field contributed to the $H$ and $LE$ fluxes measured by the mobile ET system. A two-dimensional Lagrangian random walk (LRW) model (Baldocchi, 1997) was used to estimate the flux footprint. In the LRW model, 5000 particles were released from the top of the canopy and the probability that the particles cross the sensor height at a particular distance is determined to obtain the flux footprint probability density function. The motion of a particle was determined in terms of its horizontal and vertical displacements over time calculated from the horizontal and vertical wind velocities. A random forcing term was included in the model to account for the random nature of air parcel movement. Particles returning to the release point (i.e., the top of the canopy) were perfectly reflected, thus requiring only turbulent statistics above the canopy to be modeled for the flux footprint determination. A detailed description of the flux footprint model can be found in Baldocchi (1997) and Strong et al. (2004). The time step for particle movement was considered to be 10% of the Lagrangian time scale ($T_J$) at the top of the canopy,

$$T_J = \frac{2(w)}{\epsilon}$$  \hspace{1cm} [8]

The term $\epsilon$ denotes the average rate of turbulent kinetic energy dissipation and is determined as $u'^3/0.4z$, where $z$ is the height aboveground and $u'$ is the friction velocity (Kaimal and Finnigan 1994). The Monin–Obukhov similarity relationships (Monin and Obukhov, 1954) were used to describe the behavior of the normalized standard deviation of vertical velocity ($w'$) in the inertial sublayer above the canopy. The flux footprint was estimated for the entire study period based on the maximum friction velocity observed for directional bins of 5° around the mast on the mobile ET system. Contour plots of the flux footprint probability density functions were produced by interpolating point values using a kriging procedure (Fig. 2). The peak fluxes observed by the ET system appear to originate from about 8 to 10 m from the base of the mast.

**Determining Surface Resistance**

The surface resistance $r_s$ for the fields in this study was evaluated by solving Eq. [1] using environmental conditions observed in the study fields and comparing the resulting estimates of ET with corresponding observations of ET from the mobile eddy covariance systems. An optimization procedure was used to determine $r_s$ for each field. In this procedure, Eq. [1] was solved for each of the 30-min periods in the EB data set using an arbitrarily selected value for $r_s$. The resulting set of calculated ET values was compared to the corresponding set of ET values determined from the measured values of $LE$. The difference was determined for each pair of ET values in the two sets and was used to calculate the average absolute error (AAE) according to the equation,

$$AAE = \frac{\sum_{n} |ET_m - ET_{cal}|}{n}$$  \hspace{1cm} [9]

where $ET_m$ and $ET_{cal}$ are the measured and calculated ET values, respectively, and $n$ is the number of observations. The AAE is a measure of the overall agreement between the calculated and measured values of ET. This procedure was repeated with a range of values for $r_s$. The optimum value of $r_s$ for a field was identified as the one that minimized the value of AAE.

Values of the aerodynamic resistance $r_a$ are also needed to solve Eq. [1]. These were determined from the sonic anemometer data. Output of the CSAT-3 includes horizontal wind speed $u_*$ and friction velocity $u'_*$. For each 30-min sampling period, the average values of these two quantities were determined over the period of eddy covariance measurements for each field. A graphical procedure (Monteith and Unsworth, 1990, p. 114) was then used to determine the roughness length $z_{0f}$ for each field. In this procedure, a graph is constructed with wind
speed as the abscissa and $\ln(z-d)$ as the ordinate ($z$ is the height above the ground at which wind speed is measured, and $d$ is the zero plane displacement). In this study, $d$ was estimated as 0.65$h_c$, where $h_c$ is the height of the crop canopy (Campbell and Norman, 1998, p. 71). When plotted in this graph, wind observations from various heights above the surface tend to lie along a straight line with a slope equal to $k/u^*$, where $k$ is the von Karman constant (0.41). Once the slope is calculated from the average value of $u^*$, the position of the straight line can be fixed in the graph by passing it through the average value of $u$. The intercept of this line with the ordinate axis represents $\ln(z_0)$, from which the value of $z_0$ can be calculated. The value of $z_0$ calculated for each field was considered invariant over the respective periods of EB measurements, since $h_c$ did not change appreciably over these periods. Once $z_0$ was known, the value of $r_a$ could be calculated for each 30-min sampling period from the equation (Monteith and Unsworth, 1990, p. 118),

$$r_a = \left[ \frac{\ln \left( \frac{z-d}{z_0} \right)}{k/u^*} \right]^2$$

**Estimating Crop Water Use**

Equation [6] was solved for Field 1 during Periods 1, 2, and 3 (Fig. 1) and Field 2 using observed environmental data (air temperature, wind speed, vapor pressure, and net radiation) and GC. The value of $r_{cp}$ was assumed to be 50 s m⁻¹, and $F_s$ was set equal to 1. Results were compared to corresponding values of ET determined from the eddy covariance calculations. For Field 1, the soil surface was dry during the days with eddy covariance observations. Also, the plant canopy for Field 1 almost completely covered the soil surface. Both of these factors should have limited soil evaporation, so that the values of ET determined from the eddy covariance observations were predominantly due to transpiration. Field 2 was a dryland field, and ET values used in this study were chosen from days between infrequent rainfall events to ensure that the soil surface was dry. This again should have minimized the soil evaporation component of the measured ET.

**RESULTS AND DISCUSSION**

**Crop Ground Cover**

Ground cover for Field 1 and Field 2 estimated from Landsat-5 and Landsat-7 observations during the 2008 growing season is shown in Fig. 1. The GC of Field 1 showed a steady increase through the early portion of the growing season and reached a maximum of 0.82 in early September. Following termination of the irrigation in Field 1 on Day 252, the crop exhibited a decline in GC. Ground cover for Field 2 was relatively constant throughout August and September, exhibiting a small increase following rains occurring on Days 252 and 254. The rapid decrease in GC for both fields after Day 290 was the result of chemical defoliation of the crop.

**Surface Energy Balance**

Thirty-minute averages of $R_n$ plotted vs. corresponding values of the sum of $LE$, $H$, and $G$ for Field 1, Field 2, and Field 3 are presented in Fig. 3A–C. The slope of the regression through the distribution of points in each of these graphs is an indication of the degree of closure of the steady-state EB (Eq. [7]) for that
field, with a slope of 1 indicating complete closure and a slope <1 indicating partial closure. For Field 1 (irrigated cotton) and Field 2 (dryland cotton), the slopes of the regressions were 0.78 and 0.87, respectively, suggesting closure of around 80 to 90%. These values of energy balance closure are consistent with results from other eddy covariance experiments. In a review article, Foken (2008) reported that, for a variety of land surface experiments involving eddy covariance measurements on vegetated surfaces, energy balance closures were in the range of 70 to 90%. Wilson et al. (2002) reported closure on the order of 80% for FLUXNET sites, while Mauder et al. (2006) reported closures in the range of 70 to 80% for a variety of agricultural sites. In this study, the degree of EB closure appeared to be related to the amount of vegetation at the site. As shown in Fig. 3C, the steady-state EB closure (as indicated by the slope of the regression) for the bare soil field (Field 3) was near 100%, but closure decreased for Field 2 and Field 1 with increasing GC. Residual energy terms not considered in Eq. [7] associated with the presence of a plant canopy include radiant energy used in photosynthesis and heat energy transiently stored in the canopy. Meyers and Hollinger (2004) found that the inclusion of these residual terms in the EB increased closure from 0.84 to 0.94 for a maize (Zea mays L.) crop, and from 0.90 to 0.97 for soybean [Glycine max (L.) Merr.]. Other sources of residual energy, such as contributions to vertical LE and H transport by large-scale convective eddies with periods much longer than the eddy covariance averaging period, have been suggested as candidates to close the EB (Cava et al., 2008; Foken, 2008). The results of this study suggest that large-scale eddies probably were not important in the EB, since their effect would have also led to a reduction in closure for the bare soil field (Field 3). The degree to which EB closure affects the procedure for estimating ET investigated in this study will be discussed in the next section.

**Resistances**

Figure 4 shows the results of the graphical solution for $z_0$. Measured values of canopy height ($h_c$) used in this solution were 0.8, 0.45, and 0 m for Fields 1, 2, and 3, respectively. As expected, $z_0$ for the bare field (0.45 cm) was much less than $z_0$ for either of the fields with a crop canopy (3.93 cm for Field 1 and 6.6 cm for Field 2). While the crop canopy for Field 1 was taller than that for Field 2, it presented a relatively smoother surface to airflow as it had GC close to 80%. Field 2 had GC on the order of 30 to 35%, so that the field surface was comprised of a regular pattern of rows of plants separated by intervening bare soil, with the rows oriented roughly perpendicular to the prevailing wind direction during the experiment. Since the average wind speeds for Fields 1 and 2 during the periods of EB measurements were approximately equal (see Fig. 4), Eq. [10] suggests that the difference in $z_0$ led to values of $r_s$ for Field 1 that were approximately 33% greater than corresponding values for Field 2.

Results of the optimizing procedure used to evaluate $r_s$ are presented in Fig. 5. As shown in Fig. 5A–C, the optimum values of $r_s$ for Field 1 for Periods 1, 2, and 3 were approximately 90, 110, and 290 s m$^{-1}$, respectively. The increase in $r_s$ following termination of the irrigation in Field 1 presumably was related to depletion of soil water by the cotton crop. Ground cover remained relatively constant in the dryland cotton field (Field 2) over the period of ET measurements (Day 244–277), so the entire data...
Table 2. Estimation of canopy resistance \( r_c \) from \( r_s, r_{soil} \) and ground cover (GC) for Fields 1 and 2. The value of GC is the average for days with energy balance (EB) measurements for a field. The value of \( r_{soil} \) was taken from Field 3.

<table>
<thead>
<tr>
<th>Field</th>
<th>( r_s ) s m(^{-1} )</th>
<th>( r_{soil} ) s m(^{-1} )</th>
<th>GC</th>
<th>( r_c ) s m(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field 1, Period 1</td>
<td>90</td>
<td>1225</td>
<td>0.783</td>
<td>71.6</td>
</tr>
<tr>
<td>Field 1, Period 2</td>
<td>110</td>
<td>1225</td>
<td>0.747</td>
<td>84.1</td>
</tr>
<tr>
<td>Field 1, Period 3</td>
<td>290</td>
<td>1225</td>
<td>0.614</td>
<td>196.0</td>
</tr>
<tr>
<td>Field 2</td>
<td>270</td>
<td>1225</td>
<td>0.349</td>
<td>110.0</td>
</tr>
</tbody>
</table>

set from that field was analyzed to produce a single optimum value for \( r_s \). As shown in Fig. 5D, this value was approximately 270 s m\(^{-1} \). For the bare soil field (Field 3), the optimum value for \( r_s \) was approximately 1225 s m\(^{-1} \) (Fig. 5E). This large value for \( r_s \) is consistent with the observation that the soil in this field was dry down to a depth of at least 4 cm, where the CS616 probes indicated an average volumetric water content (VWC) of 0.074 m\(^3\) m\(^{-3}\) over the period of EB measurements. This VWC is less than the upper value of residual volumetric water content \( \delta_r \) published for this soil (Baumhardt et al., 1995).

Table 2 summarizes the results of estimating \( r_s \) for Fields 1 and 2 using Eq. [2]. In these calculations, the value for \( r_{soil} \) was assumed to be determined for Field 3, because the soil surfaces for Fields 1 and 2 were also dry for days with EB measurements. In practice, once \( r_{soil} \) reaches a large value (around 1000 s m\(^{-1} \)), it makes a negligible contribution to the calculation of \( r_s \) for fields with a transpiring crop canopy. In addition, for fields with values of GC approaching 1, the term in Eq. [2] involving \( r_{soil} \) makes a small contribution to \( r_s \) regardless of the value of \( r_{soil} \). The value of \( r_s \) for Field 1 during Period 1 (71.6 s m\(^{-1} \)) approaches the published values for cotton canopy resistance under fully irrigated, unstressed conditions.

In the previous section, it was noted that complete closure of the steady-state EB was not achieved for Fields 1 and 2. Some authors (Twine et al., 2000) have suggested that closure of the EB can be forced by partitioning the residual energy between \( H \) and \( LE \), possibly in proportion to the observed Bowen Ratio. The main impact of this approach would be a reduction in the values of \( r_s \) in Table 2 calculated using the optimization procedure illustrated in Fig. 5. However, this would not have a net impact on calculating ET using the Penman–Monteith method (Eq. [1]), since the optimized values of \( r_s \) were calculated from the ET data (i.e., the two variables are not independent). Thus, we felt that forcing closure of the steady-state EB was not necessary for this investigation.

### Crop Water Use

Results of solving Eq. [6] for Field 1 during Period 1 are plotted in Fig. 6 vs. corresponding measured values of ET. Since Field 1 had almost 80% GC during this period, the measured values of \( R_n \) and the values of \( r_c \) calculated based on the estimated \( \varepsilon_0 \) (3.93 cm) for this field were used directly for \( R_{n,fc} \) and \( r_{s,fc} \) in the solution (i.e., it was felt that they should be reasonably close to the values for complete ground cover conditions). In Fig. 6, the points tend to cluster along the 1:1 line, and the line representing the simple linear regression through the distribution of points also lies close to the 1:1 line. Statistical analysis shows that the slope of the regression line is not significantly different from 1 (\( t = 0.129, 230 \text{ df}, \alpha = 0.05 \)), while the intercept of the regression line is not significantly different from 0 (\( t = -1.098, 230 \text{ df}, \alpha = 0.05 \)). This suggests that Eq. [6] provided a reasonable description of CWU for Field 1 during Period 1, and that appreciable effects associated with stomatal closure were not present during this period (i.e., setting \( F_c = 1 \) was appropriate).

Results of performing similar computations for Periods 2 and 3 for Field 1 are presented in Fig. 7 and 8, respectively. Recall that irrigation was terminated for Field 1 immediately following the Period 1. For both Periods 2 and 3, the distributions of points in the graphs fall largely below the 1:1 line, indicating that the solution of Eq. [6] for these periods with \( F_c = 1 \) generally resulted in overestimates of CWU. Both graphs show linear regressions fit to the distributions of points forced through the origin (i.e., intercept = 0). In each case, the value of the slope of the zero-intercept regression can be taken as an estimate of \( F_c \). So, \( F_c \) equaled approximately 0.86 and 0.62 for Periods 2 and 3, respectively, suggesting that appreciable effects associated with stomatal closure were present during both these periods.

Figure 9 shows the resulting estimates of CWU for Field 2 plotted against corresponding measured values of ET. Equation [6] was solved in the same manner as for Field 1, except that a few adjustments were made to certain data elements in recognition that the GC in that field (around 0.35 during the period of measurements) was well below 100%. For days on which environmental data were recorded for both Field 1 and Field 2 (see Fig. 1), analysis showed that \( R_n \) for Field 1 was on average 7% greater than \( R_n \) for Field 2. Thus, observed values of \( R_n \) used for \( R_{n,fc} \) in the solution of Eq. [6] for Field 2 were increased by 7% to make them more representative of complete ground cover conditions. For the same reason, the value of \( \varepsilon_0 \) used in calculating \( r_{s,fc} \) was decreased from 6.60 cm (the value estimated for Field 2) to 3.93 cm (the value estimated for Field 1). The distribution of points in Fig. 9 tends to cluster near the 1:1 line. The line representing the simple linear regression through the distribution of points also lies relatively close to the 1:1 line, although statistical analysis shows that its slope is different from 1 and its intercept is different from 0. On average, measured ET was approximately 0.01 mm (30 min)\(^{-1} \) greater than the estimated CWU for this field. This small bias could be the result of simplifying assumptions used in the procedure, or it...
might indicate that soil evaporation made a small contribution to the measured ET for this field. Approximately 65% of the soil surface was exposed in Field 2, as compared to only around 20% for Field 1. The average measured daytime soil evaporation rate for Field 3 (the bare soil field) during this study was 0.02 mm (30 min)^{-1}. Multiplying this by the fraction of exposed soil for Field 2 (0.65) gives a value of comparable magnitude to the average bias between measured ET and estimated CWU exhibited in Fig. 9. Of more significance is the fact that the use of Eq. [6] for Field 2 did not result in a consistent overestimate of CWU as was the case with either Period 2 or Period 3 for Field 1. This suggests that, even though Field 2 was not irrigated and had produced considerably less crop canopy than Field 1, appreciable effects associated with stomatal closure were not present in Field 2 during the study period (i.e., \( F_s \approx 1 \) for this field). The implications of this will be discussed in the next section.

### Crop Acclimation

The results presented in Fig. 6–9 illustrate the dynamic response of plants to their environment. For Field 1 during Period 1, irrigation supported lush canopy growth and high rates of CWU at or near potential levels. The value of \( F_s \) equaled 1 for this period, suggesting that the crop was acclimated with its environment and stomatal closure did not play a significant role in controlling the water status of the crop. The absence of irrigation in Field 2 resulted in much less canopy growth as compared to Field 1 (GC of 0.35 vs. almost 0.8), yet \( F_s \approx 1 \) during the study period, again indicating that the crop was acclimated to its environment.

The contrasting situation occurred for Field 1 following termination of the irrigation. During Period 2, soil water was being depleted to the degree that the cotton plants could not support the lush canopy and high rates of CWU of the previous period. The plants began to senescence leaves (as shown in Fig. 1) to reduce the rate of water loss, but they also began to close their stomata, as indicated by the value of \( F_s \) falling below 1 during this period. During Period 3, the plants continued to try to adjust to the change in their environment through increased stomatal closure and continued loss of leaf area. As shown in Fig. 1, loss of leaf area continued until, near the end of the growing season, the GC of Field 1 approached the GC of Field 2. One could imagine that, if the two fields had not been chemically defoliated shortly after Day 290, Field 1 might have re-acclimated with its environment when its GC had reached a value similar to that for Field 2 (i.e., Field 1 had become a “dryland” field).

It might be possible to directly evaluate \( F_s \) from measured environmental factors. Since \( F_s \) is associated with stomatal closure, it might be quantified through increases in canopy temperature using approaches like the Crop Water Stress Index (Jackson et al., 1981) or the Water Deficit Index (Moran et al., 1994). In this study, we did not collect the data necessary to directly evaluate \( F_s \) along these lines, but such efforts will be included in future studies.

### Potential Application

A potential use of the spectral crop coefficient approach would be in irrigation scheduling. Estimates of CWU made using this method could be used to schedule irrigation to...
replace the water lost by the crop. Such an approach would need to allow for the efficiency of the irrigation system in supplying water to the plant. To obtain values of crop GC for estimating daily CWU using Eq. [6], a model such as that described by Maas (1993) could be used to estimate daily GC from infrequent satellite observations. Imagery from Landsat-5 and Landsat-7 is currently available the day after its acquisition, and may be downloaded from the Internet. Since the purpose of the irrigation is to keep the crop plants from being water-stressed, the use of $F_s = 1$ in Eq. [6] would provide a conservative estimate of the irrigation needed to do this. A potential advantage of using this approach over the standard crop coefficient approach is that the spectral crop coefficient evaluated from remote sensing data would be unique to each individual field, and could account for nonstandard conditions.

CONCLUSIONS

Based on the results of EB measurements made in dryland and irrigated cotton fields in the Texas High Plains, CWU can be approximated by a modified version of the Penman–Monteith Equation. In this equation (Eq. [6]), the effects of GC and water stress appear as separate terms and act to reduce CWU below the potential rate calculated from environmental factors (air temperature, vapor pressure, wind speed, and net radiation). The GC term can be easily evaluated using remote sensing. The value of the $F_s$ term can be interpreted as an indicator of to what degree the crop is acclimated to its environment. This approach could find application in irrigation scheduling where irrigation is used to replace the daily CWU of a crop. In such applications, this approach might be superior to standard crop coefficient approaches because it could use remotely sensed observations of GC as a "spectral crop coefficient" that would make the resulting estimates of CWU specific to individual fields. Additional studies are needed to expand this approach to other crops, and to establish its overall accuracy.

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REFERENCES


