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Maize Evapotranspiration Estimation Using Penman-Monteith Equation and Modeling the Bulk Canopy Resistance

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Abstract: Some techniques, such as the Katerji and Perrier approach, estimate the bulk canopy resistance (r_c) as a function of meteorological variables and then calculate the hourly evapotranspiration using the Penman–Monteith equation, so that traditional crop coefficients are not needed. As far as we know, there are no published studies regarding using this method for a maize crop. The objective of this study was to calibrate and validate the canopy resistance for an irrigated continuous maize crop in the Midwestern United States (US). In addition, we determined the effect of derivation year, bowen ratio, and the extent of canopy. In this study we derive empirical coefficients necessary to estimate r_c for maize, five years (2001–2005) were considered. A split-sample approach was taken, in which each year's data was taken as a potential calibration data set and validation was accomplished while using the other four years of data. We grouped the data by green leaf area index (GLAI) and the Bowen ratio (β) by parsing the data into a 3×3 grouping: LAI (≥ 2 , ≥ 3 , and ≥ 4) and $|\beta|$ (≤ 0.1 , ≤ 0.2 , and ≤ 0.3). The best fit data indicated reasonably good results for all nine groupings, so that the calibration coefficients derived for the conditions LAI ≥ 2 and $|\beta| \leq 0.3$ were taken in light of the longer span associated with LAI ≥ 2 and the larger number of hours. For the calibrations in this subgroup, the results indicate that the annual empirical coefficients for r_c are nearly the same and equally effective, regardless of the year used for calibration. Our validation included all the daytime hours regardless of β . Thus, it was concluded that the calibration at our site was independent of the derivation year. Knowledge of the Bowen ratio was useful in calibration, but accurate ET estimates (validation) can be obtained without knowledge of the Bowen ratio. Validation resulted in hourly ET estimates for irrigated maize that explained 83% to 86% of the variation in measured ET with an accuracy of ± 0.2 mm.

Keywords: evapotranspiration; bulk canopy resistance; eddy covariance; Ithaca; NE

1. Introduction

Irrigation is the largest use of water resources in many agricultural regions of the world. The challenges of planning for water use and water resources management in a changing climate include the increased stress on the world's fresh water reserves due to increased use of water for food production, contamination of rivers, lakes, and aquifers, and a lack of support for major new water projects. There is potential need to alleviate the stress on the world's fresh water system with human population increasing and the need for more food production; conserving water through irrigation scheduling provides that potential [1].

The method, frequency, and duration of irrigation strongly affect crop yields and farm productivity [2]. An efficient use of water resources through irrigation scheduling requires an accurate estimation of crop water use to realize a potential savings.

Evapotranspiration (*ET*) estimates are required for determining timely irrigation needs when scheduling irrigation with the checkbook approach [3].

ET is one of the main components of the water cycle [4]. *ET* plays an important role in several disciplines, such as hydrology, agriculture, climatology, and meteorology [5].

The traditional approach to estimate crop *ET* is to first estimate reference *ET* from a standard surface and to apply an empirical crop coefficient, such as those that were presented by Doorenbos and Pruitt [6] and Wright [7,8]. The Penman–Monteith (PM) equation was accepted as the standard for reference *ET* by the FAO in 1990 along with a set of procedures for calculating the various parameters for short and tall crops [9,10]. The PM computes the latent heat flux (λET) as:

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \left(1 + \frac{r_c}{r_a}\right)} \quad (1)$$

where λET is the latent heat of vaporization ($\frac{MJ}{m^2t}$), Δ is the slope of the saturation vapor-pressure curve ($\frac{kPa}{^\circ C}$), R_n is the net radiation at the crop surface ($\frac{MJ}{m^2t}$), G is the soil heat flux at the soil surface ($\frac{MJ}{m^2t}$), ρ_a is the mean air density ($\frac{kg}{m^3}$), c_p is the specific heat of air at constant pressure ($\frac{MJ}{kg^\circ C}$), e_s is the saturated vapor pressure at the air temperature (kPa), e_a is the vapor pressure of air (kPa), $e_s - e_a$ is the vapor pressure deficit (kPa), γ is the psychrometric constant ($\frac{kPa}{^\circ C}$), r_a is aerodynamic resistance ($\frac{t}{m}$), and r_c is bulk canopy resistance ($\frac{t}{m}$), hereafter referred to as canopy resistance.

The PM equation, strictly speaking, applies to crops with full cover and it has been shown to be unreliable for *ET* estimates under partial cover [11,12]. Shuttleworth and Wallace provided a physically-based approach for modeling *ET* for the entire range of canopy cover [13]. However, the Shuttleworth and Wallace model requires a number of model parameters that are not commonly available [14].

When a sensitivity analysis of *ET* estimated for crops of different heights and in contrasting water status while using the PM equation was conducted, it was concluded that it is very important to correctly represent aerodynamic resistance for short crops under well-watered conditions. Canopy resistance plays a secondary role for short crops, accounting for only 10% to 25% of the variation in *ET* [15]. This could explain the good performance of simple models of canopy resistance to estimate reference grass *ET* while using the PM equation [9]. However, it was concluded that vapor pressure deficit and canopy resistance are critical in estimating *ET* for tall crops and for water stressed crops [15].

Research on *ET* has provided sound theoretical knowledge and practical applications that have been validated through field measurements. However, the transfer of theoretical advances into field practice remains far short of its potential [16,17]. Verstraeten et al. [18] provided an extensive survey on different methods to estimate ecosystem *ET* and soil moisture content and summarize the *ET* assessment techniques (from sap flow to remote sensing). Current operational approaches to estimate *ET* for an agricultural crop require crop coefficients [6–8]. Worldwide research provides crop coefficients for most existing crops as a function of phenological stage. However, variations in the accuracy of crop *ET* estimates due to the use of fixed crop coefficient values have been identified [19–21]. Differences as large as 40% between the crop coefficient derived *ET* values that were reported by Allen et al. [9] and *ET* values that were experimentally obtained have been found [22].

Several corrections have been proposed for standard crop coefficients to account for varying crop roughness values as functions of crop height, wind speed, and relative humidity [9,23,24]. Other studies proposed using a functional relationship to generate crop coefficient values that consider crop development stage and canopy density as functions of leaf area index and soil water availability [20,25]. Several researchers have developed theoretical expressions for crop coefficients based on the PM formulation to explain crop coefficient variations, and demonstrated that crop coefficients are a function of canopy resistance, aerodynamic resistance, and meteorological conditions [17,26,27]. Shuttleworth provides theoretical analyses that support the use of the PM formulation to make a direct estimation of

crop water requirements, and emphasizes the need for effective surface resistances that are equivalent to those which exists for crop coefficients, which is a major hurdle in using the PM-based approach [27].

The direct estimation of ET from the PM formulation for agricultural crops when the canopy and aerodynamic resistances (r_c and r_a) are known avoids the uncertainty associated with the use of crop coefficients [27]. The single layer or “big leaf” model assumes that latent heat lost by a crop is controlled by the entire canopy resistance to water vapor loss to the atmosphere [28]. For vegetative surfaces, r_c is the combined resistance of all leaves and soil surfaces and the resistance to vapor loss inside the canopy [27]. Meteorological and biophysical variables influenced the resistance. It has been argued that r_c has an indirect aerodynamic component, but it is often assumed that r_c mainly represents stomatal response for full canopies [29].

Bulk canopy and aerodynamic resistances have been parameterized for a reference crop, most often defined as an actively growing grass canopy of uniform height under non-limiting water conditions, but not for other crops [9]. Alves et al. proposed an approach, where the aerodynamic resistance is computed from the top of the canopy (h) to the reference height (z), where wind speed (u) and humidity are measured [30]. This expression estimates the aerodynamic resistance from the plane of momentum sink to the reference height and from the plane of momentum sink to the canopy height. Afterwards, the difference of these two values is calculated. While assuming neutral conditions, the wind speed at the top of the canopy and the wind profile under neutral stability conditions, friction velocity, is obtained [30]. An equation for the aerodynamic resistance, r_a , is resolved while using estimates of zero plane displacement height (d) [31] and roughness length (z_0) based on crop height (h), [32]:

$$r_a = \frac{\ln\left(\frac{z-d}{h-d}\right) \ln\left(\frac{z-d}{z_0}\right)}{k^2 u} = \frac{\ln\left(\frac{z-0.75h}{0.25h}\right) \ln\left(\frac{z-0.75h}{0.13h}\right)}{k^2 u} \quad (2)$$

where k is von Karman’s constant, unitless. For stable and unstable cases, stability functions are needed to calculate the aerodynamic resistance [33,34]. The height h can be estimated while using the Richards plant growth model [35]:

$$h = \frac{a_h}{(1 + e^{b_h - c_h D})^{1/d_h}} \quad (3)$$

where D is day of year and a_h , b_h , c_h , and d_h are annually derived from non-linear regression analysis.

Using Equation (2) to estimate aerodynamic resistance implies that the canopy resistance has two components: one corresponding mainly to stomatal resistance and the other to leaf boundary layer and turbulent transfer inside the canopy [17]. The use of this approach has the advantage in that it does not require any assumptions about the roughness lengths for heat and vapor transfer that may have no precise physical meaning [30].

Crop canopy resistance values are typically determined in research studies by inverting the PM equation [30], or by scaling the leaf resistance to canopy level by weighting the average stomatal resistance of the leaves by the leaf area index (LAI) [9,32]. Methods that determine the resistance through alternative means have been derived. For example, Jarvis considered that stomatal conductance (the reciprocal of resistance) is a function of environmental variables (as obtained from controlled environment studies) and their effects multiplicative [36]. Estimates using this approach have yielded good canopy resistance approximations explaining 70% of the variation; however, its use is year and site specific [37]. Alves and Pereira argue that r_c is dependent on environmental variables, so that using purely physiological approaches might not be suitable [37]. Hatfield and Allen found consistent ET estimations of cotton, grain sorghum, and grass forage, while using an empirical canopy resistance [38]. Katerji and Perrier (1983) proposed an estimate of canopy resistance as a function of an equilibrium resistance (r^*) and aerodynamic resistance (r_a), which has been used to estimate ET of alfalfa, rice, grass, lettuce, sweet sorghum, grain sorghum, soybean, tomato, and wheat [22,37,39]. Katerji and Rana found that treating canopy resistance as a constant might be acceptable in short crops, but not in taller crops, like sunflower, soybean, and sorghum [22].

A study concluded that the Katerji and Perrier approach considers a physiological component that responds to the main environmental variables in a similar way to the multiplicative method of Jarvis [36], and also considers an aerodynamic component [8]. According to Katerji and Rana [22], the work of Katerji and Perrier [39] pointed out the failure of many researchers in recognizing vapor transfer inside the canopy is a component of canopy resistance and it is dependent on wind speed. Katerji and Perrier [39] recommend a simpler alternative to the Jarvis [36] and Shuttleworth [27] methods. This approach simulates the canopy resistance by the following empirical relationship:

$$\frac{r_c}{r_a} = a \frac{r^*}{r_a} + b \quad (4)$$

where a and b are parameters to be experimentally determined by calibration when bulk canopy resistance (r_c), aerodynamic resistance (r_a), and equilibrium resistance (r^*) are known. We will refer to the evapotranspiration that was estimated from the use of r_c (Equation (4)) in Equation (1) as the Katerji Perrier evapotranspiration approach (ET_{KP}). The equilibrium resistance (r^*) is the resistance when only the radiative energy streams determine evapotranspiration, i.e., $\lambda ET_e = \frac{\Delta(R_n - G)}{\Delta + \gamma}$. Substituting this value for λET in Equation (1), r_c can be found through a relation between r_c/r_a and r^*/r_a , where the radiative controlled r^* is calculated as [17]:

$$r^* = \frac{\Delta + \gamma}{\Delta} \frac{\rho_a c_p (e_s - e_a)}{\gamma (R_n - G)} \quad (5)$$

The relation between r_c/r_a and r^*/r_a depends on the phenological stage of the vegetation and soil water status [29]. The generation of the coefficients a and b for use in Equation (4) requires an estimate of crop specific bulk canopy resistance. Inverting the PM formulation and solving for r_c we obtain:

$$r_c = r_a \frac{\Delta}{\gamma} \frac{(R_n - G)}{\lambda ET} - r_a \frac{\Delta + \gamma}{\gamma} + \frac{\rho_a c_p (e_s - e_a)}{\gamma} \frac{1}{\lambda ET} \quad (6)$$

It is suggested that an approach that estimates r_c as a function of meteorological conditions, as in Equation (4), could offer a way to overcome the limitations of applying the PM method to estimate ET [29]. The approach has been applied to estimate ET from grass, alfalfa, wheat, tomato, and rice [37]; it has received some criticism due to the need for calibrating for each location. However, it was found that the soybean coefficients a and b that were calibrated in Italy worked well for another soybean crop that was grown in France [40]. For short crops, the use of Equation (4) gave little improvement as compared to the constant r_c approach of FAO [41]. In 2011, it was shown that this semi-empirical approach of Equation (4) for r_c is capable of producing unbiased estimates of ET , while other approaches are biased too low for short crops and too high for tall crops [42]. In 2013, eight models were tested of the Jarvis type for r_c in soybean, where multiple variables, both micrometeorological (net radiation: R_n ; air temperature: T_a ; relative humidity: RH ; wind speed at 3 m: U_3 ; vapor pressure deficit: VPD ; solar zenith angle; and aerodynamic resistance: r_a) and plant variables (Leaf Area Index: LAI ; crop height: h ; and, leaf stomatal resistance r_s) were used in different combinations. The models were able to explain 66 to 93% of the variability in the measured ET that was obtained from a Bowen Ratio energy balance [43].

In 2017, the Katerji and Perrier approach was validated for rice and potato in china, the study concluded that this approach is a better alternative for estimating crop ET than the traditional FAO Penman–Monteith approach (PM) crop coefficient used [44].

Another consideration is that the formulation for r_a is only for neutral conditions. Previous studies have calibrated the method (a and b in Equation (4)) for near normal conditions. For example, in a study from Lecina et al., the calibration data was restricted to conditions of $-0.5 \leq \beta \leq 0.5$, while Alves et al. used only data with $-0.3 \leq \beta \leq 0.3$, and determined near neutral conditions while using the Richardson number [30,41].

Based on our literature review, we did not find any results, where the approach of Katerji and Perrier for estimating hourly evapotranspiration was calibrated for a maize crop. Thus, this study was undertaken. The objective of this study was to analyze the feasibility of using this approach to estimate the bulk canopy resistance for maize, a tall crop, so that the PM formulation can be directly used to estimate the hourly ET from weather data without the use of a crop coefficient. We will refer to the use of Equations (1)–(6) as the Penman Monteith Katerji and Perrier (ET_{KP}) approach. By deriving two fixed coefficients, a and b , to estimate the canopy resistance for a maize crop, the ET_{KP} from Equation (1) can provide surface ET from a canopy through the growing season on an operational basis while using weather station data and the canopy height (h). The extent to which the ET_{KP} coefficients, a and b , change from year to year for maize was determined and the accuracy with which the measured ET can be estimated while using the ET_{KP} under varying leaf area index (LAI) and under different ranks of Bowen ratio (β).

2. Materials and Methods

2.1. Study Area

The study was conducted while using data from 2001 through 2005 from a production field in the University of Nebraska Carbon Sequestration Program (CSP) [45]. The production field (41°09′54.2″ N, 96°28′35.9″ W, and 361 m), which is located in Eastern Nebraska at the University of Nebraska Agricultural Research and Development Center near Ithaca, NE, is 47 ha in size, has a center pivot irrigation system, and is maintained as a no-till continuous maize production system. The study site provides sufficient upwind fetch over a uniform cover to adequately measure mass and energy fluxes while using an eddy covariance system. We refer to the measurement of ET from this system as ET_{EC} . The soil is a deep silty clay loam that consists of four soil series: Yutan, Tomek, Filbert, and Filmore. Prior to initiating the study, the site had a 10-year history of maize-soybean rotation under no-till management. In 2001, the site was uniformly tilled (to incorporate fertilizers) by disking prior to initiating the study and it remained under no-till through 2005. Seed was planted below the crop residue from previous years and the standard best management practices were followed. The amount of N fertilizer applied was adjusted in the spring before planting to augment nitrate already in the soil, according to recommended guidelines [46]. Maize Pioneer 33P67 (Bt hybrid) was planted in 2001 and 2002, Pioneer 33B51 in 2003, and Pioneer 33B53 in 2004, all at approximately 84,000 plants ha^{-1} ; DeKalb 63–75 was planted in 2005 at approximately 82,000 plants ha^{-1} .

2.2. Field Measurements

Water was applied in the field to maintain a minimum of 50% available soil moisture in the root depth zone. The soil water conditions in the root zone were continuously monitored at four depths (0.10, 0.25, 0.5, and 1.0 m) while using Theta probes (Delta-T Devices, Cambridge, UK) at three locations within the field.

From the CSP data, we used daylight (7:30–18:30 h) growing season hourly averages of maize ET flux from eddy covariance measurements, net radiation, soil heat flux, sensible heat flux, air temperature, relative humidity, wind speed, and incoming solar radiant flux (hours during which precipitation/irrigation occurred were excluded from the study). The hourly Bowen ratios were calculated as the ratio of the sensible heat flux to latent heat flux. The measurements began around planting time in 2001 (May 14) and they have continued to the present day [47]. Net radiation (R_n) and soil heat flux (G) were available for maize at the site but they were not used in the calibration and validation, since these measurements are typically not provided from local weather stations. Thus, the methodology would be consistent with the available data to future users of the calibration coefficients. These variables were estimated in our analysis, as follows:

$$R_n = (1 - \alpha)R_s + R_{nl} \quad (7)$$

$$G = 0.1R_n \quad (8)$$

where α is the albedo of the crop (0.23), R_s is the incoming short wave radiation, and R_{nl} is the net long wave radiation that we estimate according to Allen [9], and G is the soil heat flux. The albedo for the maize crop was assumed to be 0.23; this value is also assumed for a well-irrigated short grass or a tall alfalfa crop when the reference ET is estimated [9,23].

The leaf area index (LAI) was calculated from periodic harvesting of one meter row lengths of crop measured with the LI-3100C Area Meter (Li-Cor, Lincoln, NE, USA). Samples were harvested at six plots every 10 to 14 days until the crops reached reproductive stage and again before harvest. The total and green LAI (GLAI) were calculated based upon the sorting of leaf material into green and brown components. Maize crop height was concurrently measured with measurements of leaf area. The height measurements were used in a non-linear regression to derive annual values of a_h , b_h , c_h , and d_h for use in prescribing daily height estimates (Equation (3)).

2.3. Estimating Evapotranspiration and Canopy Resistance

For each hour (7:30–18:30 Central Standard Time) during the growing season the values of r_a , r^* , and λET were used to derive the apparent canopy resistance, r_c . These data were sub-divided with attention to the GLAI and Bowen ratio ranks (β). For calibration, the values of r_c/r_a and r^*/r_a were treated as the dependent and independent values, respectively, in a linear regression. This resulted in coefficients for a and b for each year and for the defined conditions. The estimated values that exceeded $\pm 3\sigma_{est}$ were considered to be outliers and eliminated from the analysis, where σ_{est} is the standard error of the estimate.

The use of the ET_{KP} approach supposes that a full canopy is present and is contributing to the aerial and canopy resistances. Thus, data when $GLAI < 2$ were not included in our study. The data were grouped according to $GLAI \geq 2, 3$, and 4 and $|\beta| \leq 0.1, 0.2$, and 0.3 for each year from which the calibration coefficients a and b were derived. This provided a 3×3 set of coefficients for each of the years 2001 to 2005. In this manner, we determined the calibration effects of different ranks of Bowen ratio (β) and GLAI and their consistency from year to year.

The calibration coefficients a and b were applied in the validation process to the entire growing season data ($GLAI \geq 2$) for all years, with the exception of the calibration year, regardless of the Bowen ratio value.

Hourly r_c values were estimated (Equation (4)) for daylight conditions (7:30–18:30 h); nocturnal hours and hours during which precipitation occurred were excluded from the study. Some studies recommend nocturnal times be excluded, because the vapor pressure deficit and the available energy are relatively small during these times and, thus, can generate negative or undefined values for the equilibrium and canopy resistances (r^* and r_c , respectively) [29].

Estimated canopy resistance values (r_c from Equation (4)) and aerodynamic resistance, r_a , (estimated while using the Perrier model in Equation (2)) were applied in the PM equation (Equation (1)) to calculate λET (Wm^{-2}), following the recommended methods [9,48] while giving a direct approach (ET_{KP}) to estimating ET without crop coefficients. The volume of data was around 3500 values of measured hourly ET for the five years studied.

2.4. Data Analyses

The data analysis included a calibration for each year of the Katerji and Perrier approach for each stratification i.e., each combination of GLAI thresholds ($GLAI \geq 2, 3$, and 4) with each classification of Bowen ratios ($|\beta| \leq 0.1, 0.2$, and 0.3)]. The means and standard deviations of a , b , and σ were also calculated for the data within each stratification.

A split-sample approach was used in calibration and validation [49]. Coefficients a and b were derived for each year's data and used in a validation by estimating the hourly ET (ET_{KP}) for the remaining years (calibration year excluded). The performance was documented in terms of variance

explained (r^2), the standard error of estimate (σ_{est}), and bias that was present in the estimates (slope of the ET comparison curve). The calibration coefficients that produce the best overall validation (ET_{KP} compared to ET_{EC}) are assumed to be the ‘best’ values to use with a maize crop.

3. Results

In Table 1, the derived coefficients a and b for estimating r_c (Equation (4)) and the standard error of estimate for the calibrations (σ_{est}) are shown based on the combinations of GLAI and Bowen ratio (β) for each year (hours were included on the basis of GLAI thresholds ($GLAI \geq 2, 3,$ and 4) and Bowen ratio classes ($|\beta| \leq 0.1, 0.2,$ and 0.3)).

Table 1. All possible calibration combinations where three Bowen ratio ranks and three GLAI (green leaf area index) thresholds were applied to the period 2001–2005. The empirical coefficients a and b are shown along with the standard error of estimate for the best fit equation $r_c/r_a = ar^*/r_a + b$. Other statistics over the five-year period are given at the bottom of each column including the Mean, and the standard deviation (σ).

Year	GLAI \geq	$ \beta \leq 0.3$			$ \beta \leq 0.2$			$ \beta \leq 0.1$		
		a	b	σ_{est}	a	b	σ_{est}	a	b	σ_{est}
2001	2	0.67	3.15	2.43	0.73	2.36	2.24	0.74	2.15	1.95
2002	2	0.67	2.98	2.26	0.74	2.23	2.06	0.79	1.6	1.78
2003	2	0.74	2.35	2.24	0.8	1.58	2.07	0.88	0.61	1.85
2004	2	0.74	2.35	2.75	0.75	2.12	2.71	0.76	1.61	2.41
2005	2	0.75	2.56	2.91	0.8	1.96	2.77	0.88	0.93	2.69
	Mean	0.71	2.68	2.52	0.76	2.05	2.37	0.81	1.38	2.14
	σ	0.04	0.37	0.30	0.03	0.30	0.35	0.07	0.61	0.40
2001	3	0.68	2.92	2.19	0.72	2.37	2.03	0.8	1.55	1.81
2002	3	0.67	2.92	2.23	0.74	2.19	2.04	0.78	1.63	1.76
2003	3	0.73	2.37	2.25	0.79	1.62	2.08	0.88	0.61	1.85
2004	3	0.71	2.66	2.69	0.7	2.56	2.62	0.69	2.39	2.24
2005	3	0.73	2.62	2.66	0.78	2.1	2.65	0.85	1.27	2.61
	Mean	0.70	2.70	2.40	0.75	2.17	2.28	0.80	1.49	2.05
	σ	0.03	0.23	0.25	0.04	0.35	0.32	0.07	0.64	0.36
2001	4	0.67	2.95	2.24	0.72	2.33	2.07	0.79	1.55	1.84
2002	4	0.66	2.82	2.1	0.73	2.1	1.93	0.77	1.63	1.73
2003	4	0.73	2.31	2.24	0.79	1.66	2.05	0.89	0.53	1.85
2004	4	0.74	2.13	2.53	0.74	1.97	2.42	0.77	1.36	2.01
2005	4	0.75	2.41	2.76	0.82	1.66	2.71	0.92	0.42	2.55
	Mean	0.71	2.52	2.37	0.76	1.94	2.24	0.83	1.10	2.00
	σ	0.04	0.35	0.27	0.04	0.29	0.32	0.07	0.58	0.33

Figure 1 represents a typical calibration result where coefficients a and b in Equation (4) are estimated by linear regression. In this case, the solution is for the conditions $GLAI \geq 2$ and $|\beta| \leq 0.2$, which correspond to the top middle part of Table 1. The linear relationship between r_c/r_a and r^*/r_a was statistically tested for all of the cases shown in Table 1 and a statistically significant relationship was found at a 95.0% confidence level for all of the studied cases.

The standard deviation (σ) of the slope (a) across the years is a measure of the consistency of the calibration from year to year. In examining Table 1, we can see that σ for the slope for any GLAI threshold increases from $|\beta| \leq 0.3$ to $|\beta| \leq 0.1$. For example, in the case of $GLAI \geq 2$, the σ is 0.04, 0.03, and 0.07 for $|\beta| \leq 0.3, 0.2,$ and $0.1,$ respectively. Contributing to the inconsistency from year to year is the fewer number of hours in the more restrictive conditions of $|\beta| \leq 0.1$ (regardless of LAI), which result in a smaller range in r^*/r_a . For example, the mode of r^*/r_a for $|\beta| \leq 0.1, 0.2,$ and 0.3 at $LAI \geq 2$ in 2001 is 7.81, 9.17, and 22.94, respectively.

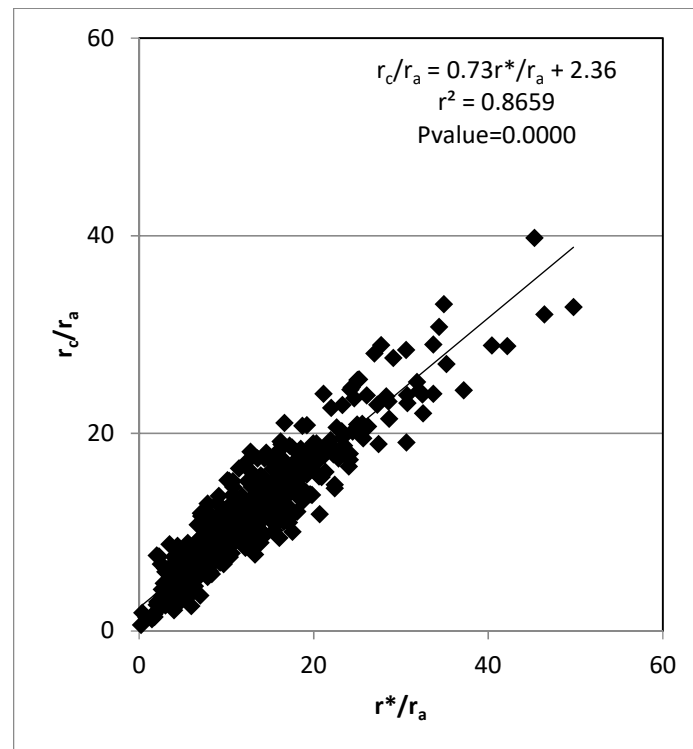


Figure 1. The calibration result for irrigated maize in 2001 with hours for calibration restricted to green leaf area index $GLAI \geq 2$ and only hours with $|\beta|$, Bowen ratio ≤ 0.2 . The variables are canopy resistance (r_c), aerodynamic resistance (r_a) and equilibrium resistance (r^*). The variation of r_c/r_a explained by r^*/r_a is 86% and the empirical coefficients are $a = 0.73$ and $b = 2.36$. p value is 0.0000.

While the magnitude of σ_{est} decreases as β gets closer to zero (i.e., values of 2.52, 2.37, and 2.14 for $GLAI \geq 2$ and $|\beta| \leq 0.3, 0.2$, and 0.1 , respectively), the standard deviation (σ) of the σ_{est} values indicate higher consistency from year to year at $|\beta| \leq 0.3$ with a value of 0.30.

Figure 2 further demonstrates the consistency among the calibration results, which shows the linear relationship between r_c/r_a and r^*/r_a . It was decided to choose the coefficients from the data group $|\beta| \leq 0.3$ and $GLAI \geq 2$ to be used in the validation of the ET_{KP} , because this case provides a larger and more consistent dataset to validate the approach.

Table 2 shows the results of the split-sample validation for $GLAI \geq 2$ and $|\beta| \leq 0.3$ for all of the years. The ET estimations using the ET_{KP} approach explained approximately 85% of the variance in the measured ET_{EC} , with a standard error of estimate about 0.2 mm for all the cases studied. This was attained without employing the β value for each hour.

The coefficients for 2003 ($a = 0.74$ and $b = 2.35$) produced an ET validation slope of 1.0 and the highest r^2 , but showed little difference in validation when compared to the other coefficient pairs. The slope of the relationship was nearly one in all cases, which indicated no bias in the estimator, demonstrating the accuracy with which ET_{EC} can be estimated while using the ET_{KP} under varying LAI conditions. As an example, the 2003 calibration coefficients were applied to all daylight growing season hours, regardless of the β value. It was excluded the 2003 data and those hours in which precipitation occurred. (Figure 3).

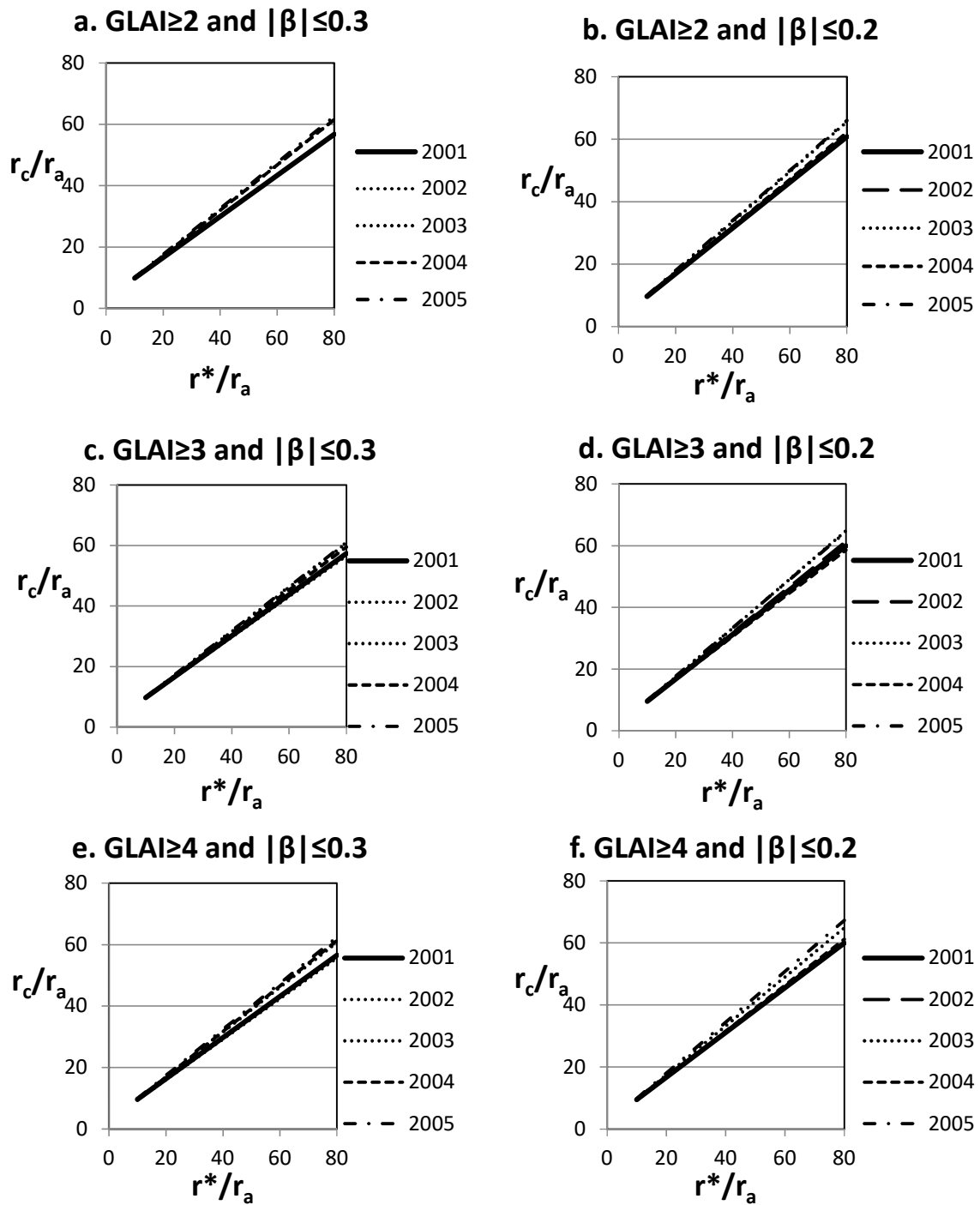


Figure 2. Regression lines resulting from a comparison of r_c/r_a to r^*/r_a from which coefficients a and b were derived for 2001–2005 while using different green leaf area index (GLAI) ranges and bowen ratio (β) combinations. The variables are canopy resistance (r_c), aerodynamic resistance (r_a) and equilibrium resistance (r^*).

Table 2. The validation of estimated hourly evapotranspiration from the Katerji Perrier approach (ET_{KP}) against measured evapotranspiration (ET_{EC}) from the eddy correlation system. The symbols indicate canopy resistance (r_c), aerodynamic resistance (r_a), and equilibrium resistance (r^*). The empirical coefficients necessary to estimate r_c for maize in each of the five years were derived ($r_c/r_a = ar^*/r_a + b$). A and B and σ_{est} (validate) are from the linear regression between ET_{EC} and ET_{KP} . Calibration years and coefficients are repeated here from Table 1 and shown on the left. Validation data includes all hours from 730 to 1830 CST with LAI ≥ 2 , regardless of thermal stability. No hours from the calibration year were included in the validation.

Year	Calibration $r_c/r_a = ar^*/r_a + b$			Validation ET_{EC} Measured Vs ET_{KP} Estimated			
	a	b	σ_{est}	r^2	σ_{est} (validate)	A	B
2001	0.67	3.15	2.43	0.83	0.21	0.97	0.04
2002	0.67	2.98	2.26	0.85	0.20	0.99	0.01
2003	0.74	2.35	2.24	0.86	0.20	1.00	0.01
2004	0.74	2.35	2.75	0.85	0.20	1.00	0.01
2005	0.75	2.56	2.91	0.85	0.20	1.01	0.02

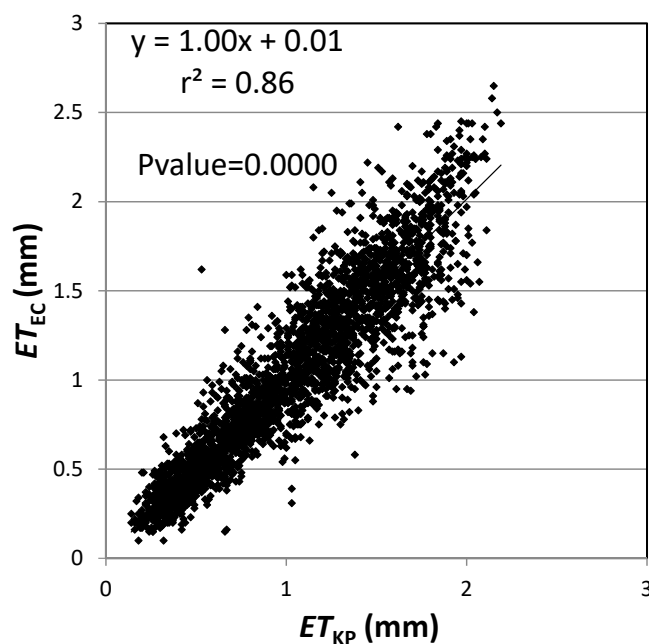


Figure 3. Validation of ET_{KP} against ET_{EC} for hours when GLAI ≥ 2 using the 2003 coefficients with slope, r^2 , and σ_{est} of 1.0, 86%, and 0.20 mm, respectively, for all hours, regardless of β value. ET_{EC} is the ET measured by the eddy correlation approach and ET_{KP} is the estimated ET from the Penman Monteith equation with the Katerji and Perrier approach [19] for canopy resistance.

4. Discussion

Some techniques estimate the bulk canopy resistance (r_c) as a function of meteorological variables and then calculate the hourly evapotranspiration while using the Penman–Monteith equation so that traditional crop coefficients are not needed. The objective of this study was to calibrate and validate the canopy resistance for an irrigated continuous maize crop. In addition, the effect of derivation year, bowen ratio, and the extent of canopy was determined. The empirical coefficients that were necessary to estimate r_c for maize in each of the five years (2001–2005) were derived. A split-sample approach was taken in which each year's data was taken as a potential calibration data set and validation was accomplished while using the other four years of data.

The data was grouped by green leaf area index (GLAI) and the Bowen ratio (β) by parsing the data into a 3×3 grouping: LAI (≥ 2 , ≥ 3 , and ≥ 4) and $|\beta|$ (≤ 0.1 , ≤ 0.2 , and ≤ 0.3). The best fit data indicated reasonably good results for all nine groupings, so the calibration coefficients that were derived for the conditions LAI ≥ 2 and $|\beta| \leq 0.3$ were taken in light of the longer span that was associated with LAI ≥ 2 and the larger number of hours. The results indicate the annual empirical coefficients for r_c are nearly the same and equally effective, regardless of the year used for calibration, for the calibrations in this subgroup. Our validation included all daytime hours, regardless of β . Thus, it was concluded that the calibration at our site was independent of the derivation year. This is consistent with the findings by Rana and Katerji [40], proposing that calibration shows an interannual stability. Knowledge of the Bowen ratio was useful in calibration, but accurate evapotranspiration estimation can be obtained without knowing it. Validation resulted in hourly ET estimation for irrigated maize that explained 83% to 86% of the variation in measured ET with an accuracy of ± 0.2 mm.

A limitation of the ET_{KP} approach is that the method worked reasonably well for well watered conditions and with LAI bigger than 2. It is necessary to investigate an approach that could be used for LAI smaller than 2; in such conditions, the soil is not full covered and the soil evaporation is important for the ET estimation. The canopy height is needed, but it is not a difficult value to observe in an operational sense. Future work should include additional comparisons of the calibration coefficients across sites with different climates and across hybrids of maize before a common use of this method. Additionally, it is necessary to validate whether the approach can be used or not under rainfed conditions.

The main advantage of the proposed method is that uncertainties that were introduced when estimating the crop ET using a crop coefficient will be avoided; however, it is necessary to first calibrate the method before using it. An advantage of the present study with respect to other studies is the volume of data used, five years of information were used in the validation of the ET_{KP} approach, under different LAI conditions and Bowen ratio values. Our study showed that the calibration was independent of the derivation year.

5. Conclusions

It was concluded that hourly estimates of ET for maize in daylight hours can be made without systematic bias over multiple years. The validation results indicate that the calibration year does not affect the performance of the technique. Note that the Bowen ratio was not used in the validation, so, although the calibration should be conducted with the knowledge of the Bowen ratio, the application does not require knowing it.

The results that are presented in this study show that it is possible to use the ET_{KP} formulation to obtain an unbiased estimate of maize ET when the GLAI is 2 or above and for the Bowen ratio ranks analyzed ($|\beta| \leq 0.3$).

The results indicate that the annual empirical coefficients to estimate the canopy resistance are nearly the same and equally effective, regardless of the year used for calibration. The validation of the ET_{KP} method resulted in hourly ET estimates for irrigated maize that explained 83% to 86% of the variation in measured ET with an accuracy of ± 0.2 mm. This study concludes that reliable maize crop evapotranspiration can be made without the use of crop coefficients.

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