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EVALUATION OF SIMULATION-BASED METHODS FOR ESTIMATING TRANSPIRATION-USE EFFICIENCY OF WHEAT AND MAIZE

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Abstract: In a previous research, (Kremer and Stöckle, 2012), developed equations to estimate crop transpiration–use efficiency (w, g CO_2 kg^{-1} H_2O), to determine parameters used in simple approaches to estimate (w, g CO_2 kg^{-1} k_{Da} H2O kPa; k_{ETo}, g CO_2 m^{-2} ground area). These equations assess w, k_{Da}, and k_{ETo}, as a function of climatic conditions represented by daytime air vapor pressure deficit (Da) or reference crop evapotranspiration (ETo). To develop the equations, simulations using a mechanistic canopy transpiration and photosynthesis model were performed using weather data from eight world locations with contrasting climate, but these simulations are a first approximation to overcome the spatial transferability of w, k_{Da}, k_{ETo} and , however field validation will be required before adoption, for that reason, these equations expressed in terms of CO_2 assimilation per unit ground area were converted to aboveground biomass per unit ground area using a conversion factor f_{abg} (0.36 for wheat, and 0.33 for maize), and evaluated with available field data. Experimental w data in the literature are not only scarce, but they are highly variable due to differences in cultivars, crop management, methods to estimate crop transpiration and biomass, and other sources of variability. Despite these limitations, the simulation–based equations to estimate w and k_{Da} of wheat and maize appeared to be robust estimators of observed values, while k_{ETo}, for maize has a good tendency however is needed more field data to be more conclusive.

Keywords: Transpiration use-efficiency, models of biomass production.

INTRODUCTION

Crop transpiration–use efficiency (w), defined as the ratio of biomass (B) produced per unit of water transpired (T), has been used to evaluate crop productivity as a function of water supply. A few approaches have been proposed to estimate w as a function of climatic conditions. Two of these approaches will be considered here:

$$w = \frac{k_{Da}}{D_a}; \text{ (Bierhuizen and Slatyer, 1965; Tanner and Sinclair, 1983)} \quad (1)$$

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$$w = \frac{k_{ETo}}{ET_o}\text{; (Steduto and Albrizio, 2005)} \qquad (2)$$

where k_{Da} and k_{ETo} are crop–dependent parameters, D_a is the daytime air vapor pressure deficit and ET_o is the reference crop evapotranspiration (Allen *et al.*, 1998). It is commonly accepted that both k_{Da} and k_{ETo} are reasonably conservative so that values determined experimentally in one location can be readily transferred to another (Ehlers and Goss, 2003) while D_a and ET_o (Equatios (1) and (2), respectively) will account for the effect of climatic differences on w. Equations 1 and 2 have been used and accepted as reasonable predictors of w (eg. Stöckle et al., 1994; Sinclair and Seligman, 1995; Steduto and Albrizio, 2005). However, concerns about the transferability of k_{Da} have been raised recently (Kemanian et al., 2005), while Steduto and Albrizio (2005) have claimed that k_{ETo} is a more stable and transferable parameter than k_{Da}.

In previous researches of this group (Kremer and Stöckle, 2012), the transferability of k_{Da} and k_{ETo} was tested for well-developed and non-stressed crops using a mechanistic canopy transpiration and photosynthesis model (CTP) (Kremer; 2006). The model was applied using data from eight world locations to determine k_{Da} (g CO_2 $kg^{-1}H_2O$ kPa) and k_{ETo} (g CO_2 m^{-2} ground area) values for wheat and maize. The results of this analysis indicated that these parameters were not stable, but tended to increase along climatic gradients represented by increasing D_a (kPa) or ET_o (mm day^{-1}). In the later, equations were proposed to estimate w, k_{Da} and k_{ETo} as a function of D_a or ET_o. These equations, obtained by computer simulation, require field verification before they can be used.

The CTP model calculates w as mass of CO_2 assimilation per mass of water transpired, which cannot be compared directly with literature data usually expressed as aboveground biomass produced per mass of water transpired. To transform CO_2 assimilation to aboveground biomass production, Monteith (1981) suggested that: 1) the biomass produced by a crop can be assumed a constant fraction of CO_2 assimilation, and, 2) the fraction of CO_2 assimilation loss by respiration (f_r) is often 0.35 to 0.45. Therefore, as a first approximation, the following factor times CO_2 assimilation would estimate biomass production:

$$f_{DM} = 0.682(1 - f_r) \qquad (3)$$

where 0.682 is the ratio of molecular weights of CH_2O and CO_2.. To estimate aboveground biomass, the fraction of biomass apportioned to the roots has to be discounted. Thus, the conversion factor of mass of CO_2 fixation to aboveground biomass is given by:

$$f_{abg} = \frac{0.682(1-f_r)}{(1+r)} \tag{4}$$

where r is the root to shoot fraction. Considering a r value for wheat and maize of 0.20 to 0.30 (Lorenz and Lal, 2005), f_{abg} should range between 0.29 and 0.37. Using w field data collected (wheat and maize) at the Conservation and Production Research Laboratory, Bushland (35°11' N, 102°06' W; elevation 1170 m a.s.l.), Texas, USA, and w (g CO_2 kg^{-1} H_2O) from the simulation-based equations (Kremer and Stöckle, 2012), f_{abg} was optimized and determined to be 0.36 and 0.33 for wheat and maize, respectively. Thus, the equations from Kremer and Stöckle (2012) to estimate w (g kg^{-1}), k_{Da} (Pa) and k_{ETo} (g m^{-2}), expressed in terms of aboveground biomass are:

$$w_{wheat} = 4.65\ D_a^{-0.51} \tag{5}$$

$$w_{maize} = 6.77\ D_a^{-0.34} \tag{6}$$

$$k_{Dawheat} = 1.57 D_a + 2.89 \tag{7}$$

$$k_{Damaize} = 3.54 D_a + 3.04 \tag{8}$$

$$k_{ETowheat} = 0.54 ET_o + 16.82 \tag{9}$$

$$k_{ETomaize} = 2.58 ET_o + 17.45 \tag{10}$$

As mentioned, the simulation-based equations presented here are offered as a first approximation to overcome the spatial transferability of w, k_{Da}, and k_{ETo}, but field validation will be required before adoption is recommended, for that reason, the main objective of this work was to evaluate the validity of these equations to estimate w, k_{Da} and k_{ETo} across climatic conditions through comparison with field data.

MATERIALS AND METHODS

Experimental data suitable for the calculation of w, k_{Da}, and k_{ETo} were obtained from published articles and direct communication with selected researchers. In a few instances, experimental values for these parameters were readily available, but in most cases they were derived from raw data. The quality of the available data differed and was classified as follows: a) complete data set available including daily crop transpiration, crop above ground biomass accumulation, and daily measurements of global solar radiation (MJ m^{-2} s^{-1}), air temperature (^{o}C), air relative humidity and wind speed; b) daily crop transpiration was not reported; c) data set includes daily crop evapotranspiration instead of transpiration, and d) crop transpiration and biomass are presented as total for the period, and D_a and ET_o are averaged for the same period. For type (a) no additional effort was needed and k_{Da} and k_{ETo} were estimated as the slope of the linear regression between biomass accumulation and the daily integration of the quotient transpiration to daytime D_a (eg. Tanner, 1981; Condon et al., 1993; Kemanian et al., 2005) or the daily integration of the quotient transpiration to ET_o (e.g. Steduto and Albrizio, 2005). For type (b), daily crop transpiration was simulated using the CTP model, and k_{Da} and k_{ETo} were estimated with the regression method explained in (a). For type (c), crop transpiration was computed as: $T = ET(1-\tau_{bt})$, where T is crop transpiration, ET is the measured evapotranspiration and τ_{bt} is the estimated fraction of incident beam irradiance that penetrates the canopy and reaches the soil surface. The k_{Da} and k_{ETo} were computed with the regression method. For type (d), k_{Da} and k_{ETo} were reported or estimated as the product of w times D_a or ET_o. Transpiration–use efficiency in all the cases was estimated as the quotient between total aboveground biomass and transpiration for the period tested. Daytime D_a was computed as 2/3 of the maximum D_a for each day (e.g. Kemanian et al., 2005), determined from maximum temperature and minimum relative humidity. Daily ET_o calculations were carried out daily as proposed by Allen et al. (1988). Tables 1, 2 and 3 summarize the available data and their quality type.

Evaluation of the simulation-based equations

Qualitative evaluation of the performance of the simulation–based equations to estimate w and k_{Da} as a function of D_a, and k_{ETo} as a function of ET_o, was performed through graphical inspection, considering the trend of the observed (Tables 1, 2 and 3) and simulation-based values.

The use of the simulation–based equations for actual field applications was tested by comparing their estimations with that of similar equations developed from observed data. The comparative analysis was performed by sampling from field and simulation-based equations at fixed intervals along a climatic gradient represented by D_a or ET_o within a range typical for commercial growth of wheat or maize and where most of the observed data were collected. The comparison was quantified as follows:

$$\overline{D}_e = 100\, n^{-1} \sum_{1}^{n} \left(\frac{abs(S_i - F_i)}{S_i} \right) \qquad (11)$$

where $\overline{D}_e$ is the average relative difference of estimation (percent), S_i is the w, k_{Da} or k_{ETo} values estimated with simulation–based equations, F_i is the w, k_{Da} or k_{ETo} values estimated with the observation–based equations, and n is the number of pair of data. A low $\overline{D}_e$ implies that the mean difference along the weather gradient of parameters estimated with the observation– and simulation–based equations is low, and vice versa.

RESULTS AND DISCUSSION

Simulated and observed data points of transpiration–use efficiency, plotted as a function of daytime D_a , are shown in Figure 1. The scattering of the simulated points is an indication of other climatic sources of variability that remain unexplained. Overall, the simulated and observed values present a similar trend, but with larger scattering of the latter. The scattering of observed data is enhanced by differences in varieties, crop management; methods to estimate crop transpiration, biomass sampling method, other sources of experimental error, and methods of calculation (see data quality). The comparative analysis was limited to the observed range of climatic variability. In the case of wheat, the observed w data are concentrated in the 0.5 to 1.6 kPa D_a range, with a 60% of the data from environments with D_a lower than 1kPa. Maize is grown in a wider range of conditions (1 to 3.3 kPa). Figure 1 shows power functions fitted to the observed and simulated w values as function of D_a. These equations are similar, particularly in the case of wheat. For wheat the index $\overline{D}_e$ had value of 4.8%, and a maximum value (n=1) of 9.2% at 1.6 kPa, whereas for maize a mean value of 6.5% and a maximum value (n=1) of 12.3% at 3.3 kPa was found. It can be concluded that the variability of w with D_a is supported by observed and simulated data, and that the simulation–based equations can be used as a tool to transfer w across climatic conditions beyond that covered by available field data.

Figure 2 presents observed and simulated values of k_{Da}, showing a good visual agreement between the two sets of values. This Figure includes linear regressions of observed and simulated k_{Da} values as a function of D_a. Again, the comparative analysis was limited to the range of climatic variability of the observed data. The equations are very similar, in fact remarkably similar in the case of wheat. For wheat the index $\overline{D}_e$ had a value of 2.5% and a maximum value (n=1) of 3.8% at 0.5 kPa , whereas for maize had a value of 4.8% and maximum value (n=1) of 8.9% at 3.3 kPa. These results indicate that: a) k_{Da} is not a constant across a climatic gradient, b) the variation of k_{Da} with D_a is supported by simulated and observed data, c) the simulated linear equations , which includes a wider range of climatic conditions, can be used as tool to extrapolate experimentally–determined k_{Da} values or to select k_{Da} values for estimation of w and crop productivity, and d) the use of the CTP model as a means to determining k_{Da} values for crops other than wheat and maize appears promising and would constitute a valuable tool, particularly considering that data is limited or nonexistent for most crops.

Kremer and Stöckle (2012), concluded that, in the case of wheat, an average k_{ETo} value could be used as a constant regardless of climatic differences. However, it was not possible to get enough confident field data to probe that affirmation. In the case of maize, the available observed data was also scarce, but its ET_o range was wider (4.5 to 13 mm day^{-1}), allowing a better comparison. Figure 3 shows a good visual agreement of simulated and observed k_{ETo}. Dispersion of observed data for maize followed the same trend that the simulated data. A Linear regression of observed and simulated k_{ETo} values for maize as function of ET_o is presented showing a similar tendency. The index $\overline{D}_e$ had a value of 6.4 % and a maximum value (n=1) of 12.3% at 13.04 mm day^{-1}. It can be concluded that, in the case of maize, the variation of w with ET_o is supported with observed and simulated data, and that the simulation–based equation can be used as a tool to transfer experimentally–determined values to other locations.

CONCLUSIONS

The validity of the simulation–based equations to estimate w and k_{Da} as functions of D_a , and k_{ETo} as a function of ET_o was demonstrated using observed data from different sources.

The simulation–based power equations to estimate w as function of D_a for wheat and maize showed to be reliable estimators, with the variation of w with D_a being supported by both observed and simulated data.

The simulation–based linear equations to estimate k_{Da} as a function of D_a showed to be robust estimators of the observed values for wheat and maize, with D_a able to explain most of the variation of k_{Da} across a wide climatic range. Their use to extrapolate experimentally–

determined k_{Da} values or to select k_{Da} values for estimation of w and crop productivity is supported by these results.

The performance of functions to estimate k_{ETo} could not be tested with sufficient data, however some comments can be made. In the case of maize k_{ETo} maize appeared well correlated with variations of ET_o.

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Tables and Figures

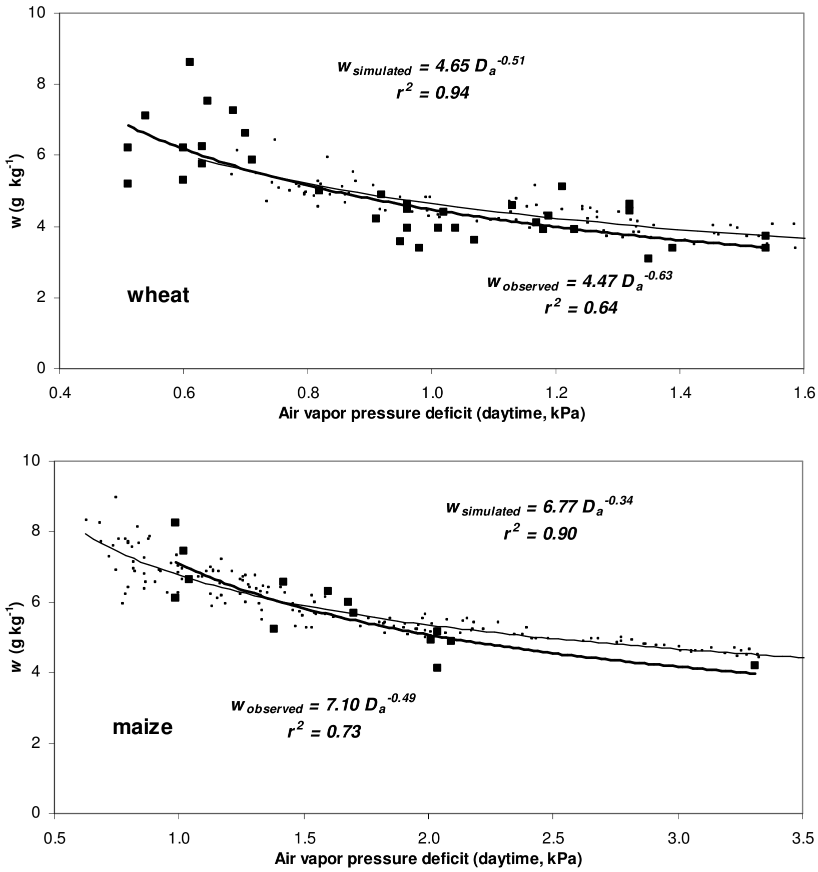

Figure 1. Variability w as a function of the vapor pressure deficit (daytime; kPa) for wheat and maize. -: simulated data; ■: observed data; — : fitted line for simulated data; ▬: fitted line for observed data.

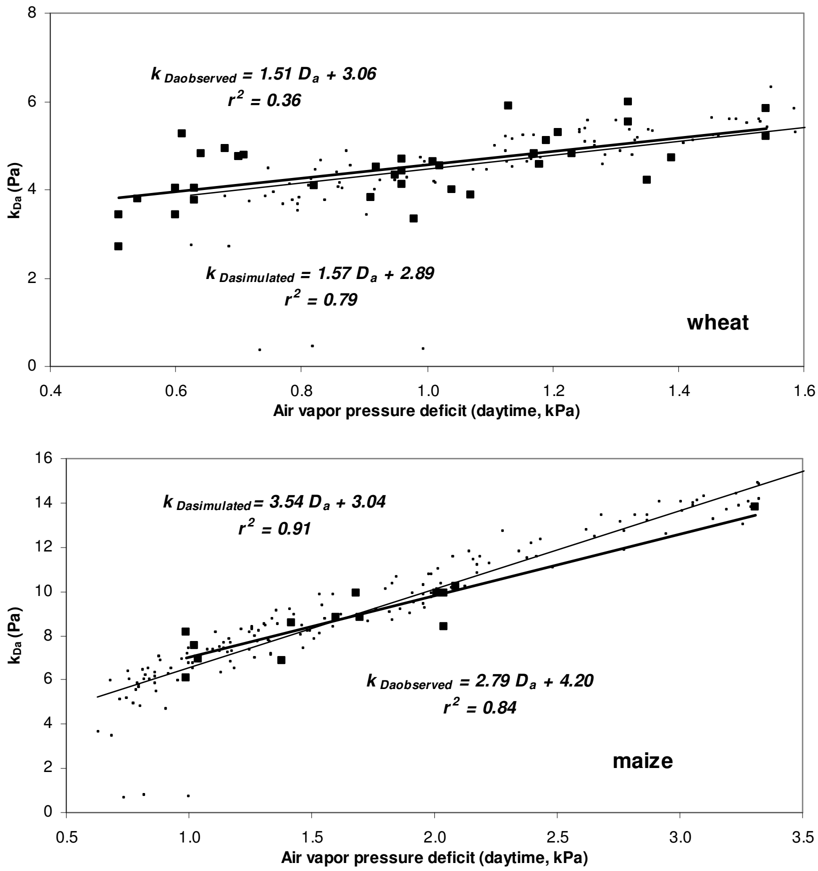

Figure 2. Variability of k_{Da} (Pa) as a function of the vapor pressure deficit (daytime; kPa) for wheat and maize. -: simulated data; ■: observed data; — : fitted line for simulated data; ▬: fitted line for observed data.

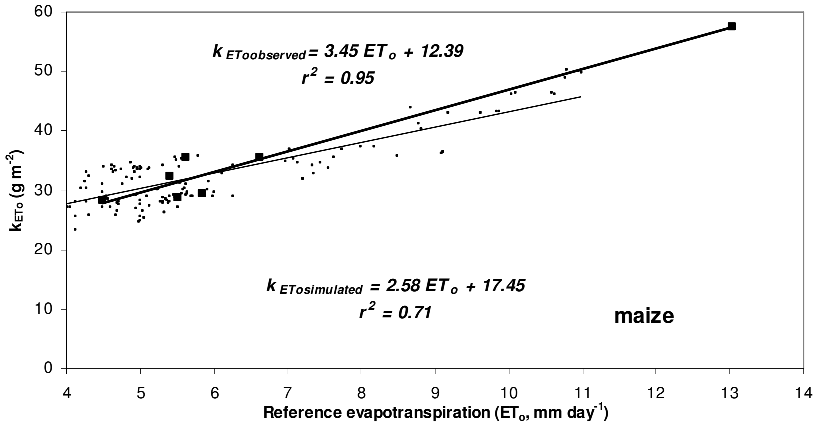

Figure 3. Variability of k_{ETo} (mm day−1) as a function of the reference evapotranspiration (ETo) for maize. -: simulated outputs; ■: observed data; — : fitted line for simulated data; ▬: fitted line for observed data.

Table 1. Wheat transpiration use efficiency (w) and k_{Da} as reported or calculated from data obtained in literature. Q refers to the quality of the data as described in the text.

Source	Site	Q	variety	w(gkg^{-1})	k_{Da}(Pa)	D_a (kPa)	observations
(1)	Mederrin, Australia	d	Gutha	4.61	4.43	0.96	1987
			Gameny	4.49	4.67	0.96	
			Purple Straw	3.95	4.11	0.96	
(2)		d	Timgalen	5.00	4.08	0.82	1973,D1,preanthesis
				4.30	5.10	1.19	1973,D1,postanthesis
				4.90	4.50	0.92	1973,D2,preanthesis
				3.90	4.80	1.23	1973,D2,postanthesis
				3.60	3.87	1.07	1973,D3,preanthesis
				3.10	4.20	1.35	1973,D3,postanthesis
				4.20	3.81	0.91	1975,D1,preanthesis
				4.10	4.80	1.17	1975,D1,postanthesis
				3.40	3.33	0.98	1975,D2,preanthesis
				3.40	4.73	1.39	1975,D2,postanthesis
(3)	Werribee, Australia	d	Bank	6.60	4.74	0.7	1984
				7.53	4.82	0.64	1985
			Quarrion	7.24	4.93	0.68	1984
				8.61	5.26	0.61	1985
(4)	Moombooldool, Australia	a	Gutha	7.10	3.80	0.54	1985, preanthesis
			Quarrion	5.87	4.79	0.71	
(5)	Toowoomba, Australia	d	Hattog	3.93	4.58	1.18	1993
(6)	Nottinghamshire, UK	d	Soissons	5.29	3.44	0.6	1994
				5.77	3.75	0.63	1995
			Maris Huntsman	6.20	4.03	0.60	1994
				6.22	4.04	0.63	1995
(7)	Pullman, WA	a	WB926R	4.59	5.90	1.13	Pooling 1998/1999
(8)	Bushland, TX	c		5.10	5.30	1.21	1989/90

				3.94	4.63	1.01	1991/93 North E Lysimeter
				3.59	4.32	0.95	1991/92 SE Lysimeter
				3.94	4.00	1.04	1992/93 NW Lysimeter
				4.38	4.55	1.02	1992/93 SW Lysimeter
(9)	Aleppo, Syria	b	Cham1	4.45	5.53	1.32	1990
			Huarina	4.64	6.00	1.32	1990
(10)	Pucawan, Australia	d	Average	6.20	3.43	0.51	preanthesis, low N
			Cometz,	5.20	2.70	0.51	preanthesis, high N
			Janz and	3.74	5.83	1.54	postanthesis, low N
			Kulin	3.39	5.22	1.54	postanthesis, high N

(1) Siddique et al. (1990); (2) Doyle and Fischer (1979); (3) Connor et al. (1992); (4) Condon et al. (1993); (5) Meinke et al. (1977); (6) Foulkes et al. (2001); (7) Marcos (2000); (8) Howard, T. (personal communication) (9) Pala et al. (1996); (10) Angus and van Herwaarden (2001).

Table 2. Maize transpiration use efficiency (w) and k_{Da} as reported or calculated from data obtained in literature. Q refers to the quality of the data as described in the text**.**

Source	Site	Q	variety	w(gkg^{-1})	k_{Da} (Pa)	D_a (kPa)	observations
(1)	Logan, UT	d	Utahybrid 544a and NKPX–20	4.12	8.4	2.04	1974/1975
	Ft. Collins, CO	d	NKPX–20 and Pioneer 3955	4.88	10.2	2.09	1974/1975
	Davis, CA	d	Funks 4444	4.93	9.9	2.01	1974/1975
(2)	Elora, ontario	d	PAG SXIII	6.12	6.06	0.99	1981– low density
				8.25	8.16	0.99	1981–high density
				6.64	6.93	1.04	1982–high N
				7.44	7.55	1.02	1982–low N
(3)	Davis, CA	c		5.14	9.92	2.04	1974
(4)	Prosser, WA	b		6.01	9.90	1.68	2004 –early seeding
				6.3	8.85	1.6	2004 –late seeding
(5)	Bushland, TX	c	Pioneer 3124	6.56	8.58	1.42	1990 North East Lysimeter
			Pioneer 3245	5.69	8.81	1.7	1990 South East Lysimeter

			Pioneer 3245	5.21	6.88	1.38	1994 North West Lysimeter
(6)	Lebanon , Bekaa valley	d	Manuel	4.18	13.83	3.31	1998

(1) Ehlers and Goss (2003), extracted from Tanner and Sinclair (1983); (2) Walker (1986); (3) Acevedo (1975); (4) Kremer (2004, not published); (5) Howard, T. (personal communication); (6) Karam et al. (2003).

Table 3. Maize transpiration use efficiency (w) and k_{ETo} as reported or calculated from data obtained in literature. Q refers to the quality of the data as described in the text.

Source	Site	Q	variety	w(gkg^{-1})	k_{ETo} (gkg^{-1})	ET_o(mmday^{-1})	Observations
(1)	Davis, CA	c		5.14	29.5	5.84	1974
(2)	Prosser, WA	b		6.01	32.36	5.41	2004–early seeding
				6.3	28.32	4.50	2004–late seeding
(3)^{bc}	Bushland, TX	c	Pioneer 3124	6.56	35.46	5.62	1990NE Lysimeter
			Pioneer 3245	5.69	35.53	6.62	1990SE Lysimeter
			Pioneer 3245	5.21	28.80	5.52	1994SE Lysimeter
(4)	Lebanon , Bekaa valley	d	Manuel	4.18	57.54	13.04	1998

(1) Acevedo (1975); (2) Kremer (2004, not published); (3) Howard, T. (personal communication) (4) Karam et al. (2003).