TECHNICAL NOTE:

NON-WATER-STRESSED BASELINES FOR CALCULATING CROP WATER STRESS INDEX (CWSI) FOR ALFALFA AND TALL FESCUE GRASS

J. O. Payero, C. M. U. Neale, J. L. Wright

ABSTRACT. *The lack of transferability of the Crop Water Stress Index (CWSI) baselines, together with the restriction of having to make required measurements close to noon and under clear-sky conditions, are major drawbacks that restrict the use of the empirical CWSI method for irrigation scheduling. The objectives of this study were to: (1) evaluate the effect of solar radiation (R_s) on the non-water-stressed baselines (NWSBs) of alfalfa (*Medicago sativa *L.) and tall fescue grass (*Festuca arundinacea*), and (2) develop empirical equations to estimate their NWSBs, which could be applied at any time during the daytime cycle and under conditions of full canopy cover. A Bowen ratio system was used to measure 20 min averages of radiometric surface temperature, air temperature (T_a), wind speed (u_2), dew point, and R_s over the two crop canopies during the 1991 growing season at Kimberly, Idaho. Using this dataset, empirical NWSBs for different R_s ranges were derived, which tended to diverge from each other as vapor pressure deficit (VPD) increased, indicating that R_s considerably affected the baselines and that its effect was more pronounced as the air got drier. Multiple regression analysis was also used to develop equations to estimate the NWSBs for the entire daytime cycle and specifically for the near-noon period. For alfalfa, the equation derived for the entire daytime cycle estimated the NWSBs as a function of R_s, VPD, T_a, u_2, and plant canopy height (h) ($r^2 = 0.89$). For grass, the equation only included R_s, VPD, T_a, and u_2 ($r^2 = 0.89$). For alfalfa, the near-noon equation included R_s, VPD, T_a, u_2, and h ($r^2 = 0.92$). For grass, on the other hand, T_a and h were not statistically significant, and the near-noon equation only included VPD, R_s, and u_2 ($r^2 = 0.94$). Since all variables that significantly affected the NWSBs for these crops were included in the equations, we expect them to be transferable to other locations; however, additional testing at other locations is needed to confirm this hypothesis.*

Keywords. *Alfalfa, Bowen ratio, Canopy temperature, CWSI, Infrared thermometer, Irrigation scheduling, Tall fescue grass, Water stress.*

Canopy temperature measured with infrared thermometers is often promoted as a basis for irrigation scheduling (Geiser et al., 1982; Stanghellini and Lorenzi, 1994; Wanjura and Upchurch, 1996; Wanjura and Upchurch, 2000; Wanjura et al., 2003; Bockhold et al., 2003; Colaizzi et al., 2003). Although this technology has a long history of development, it is yet to be adopted by farmers to schedule irrigations. Wolpert (1962) was among the first to study the factors affecting canopy temperature, using a theoretical mathematical representation of all the variables important to the heat balance of a plant leaf. Gates (1964) and Linacre (1964) recognized that transpiration was an important factor controlling leaf temperature, as it acts as a cooling mechanism. At that time, canopy temperature was measured using thermocouples embedded in the leaves, which was not very practical for general use. The use of infrared thermometers to measure canopy temperature, however, was becoming feasible (Conaway and van Bavel, 1967; Fuchs and Tanner, 1966). Carlson et al. (1972) recognized that canopy temperature provided a measure of the plant response to its environment and suggested that the factors affecting canopy temperature were the same ones affecting evapotranspiration. These factors included wind speed, solar radiation, air temperature, vapor pressure deficit, and soil moisture.

Linking canopy temperature to soil moisture was particularly important since the potential of using canopy temperature as an indicator of crop water stress and as a tool for irrigation scheduling was then recognized. The basic assumption was that transpiration cools the leaves and as available soil moisture decreases, transpiration is reduced and, therefore, the temperature of the leaves increases. Considerable research followed, trying to use canopy temperature as a tool for irrigation scheduling, and many indexes were developed to relate canopy temperature to crop water stress (Idso et al., 1977; Jackson et al., 1977; Blad et al., 1981). Ehrler (1973) made the seminal observation that canopy minus air temperature ($T_c - T_a$) was lineally related to air vapor pressure deficit (VPD) and Ehrler et al. (1978) demonstrated that ($T_c - T_a$) was a reliable indicator of plant water stress by relating it to measured plant water potential. Idso et al. (1981) realized that lower and upper baselines could be established empirically for both non-water-stressed and for non-transpiring crop conditions, respectively. They used these baselines to calculate what they called the Crop

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Article was submitted for review in May 2004; approved for publication by the Soil & Water Division of ASAE in February 2005. A contribution of the University of Nebraska Agricultural Research Division, Lincoln, NE 68583, Journal Series No. 14589.

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Transactions of the ASAE

Vol. 48(2): 653−661

2005 American Society of Agricultural Engineers ISSN 0001−2351

Water Stress Index (CWSI) as an indicator of crop water stress. This empirical CWSI is calculated as (Idso et al., 1981):

$$\text{CWSI} = \frac{(T_c - T_a)_m - (T_c - T_a)_{LB}}{(T_c - T_a)_{UB} - (T_c - T_a)_{LB}} \tag{1}$$

where the subscripts m, LB, and UB refer to the $(T_c - T_a)$ values for the measured, lower baseline, and upper baseline, respectively.

Jackson et al. (1981) and Jackson (1982) established the theoretical basis for the CWSI. They showed that the lower baseline was a function of net radiation, crop resistances (both aerodynamic and surface), and vapor pressure deficit, while the upper baseline was a near-horizontal line that depended on available energy and crop aerodynamic properties. This theoretical approach then requires knowledge of crop resistance properties and net radiation, in addition to measured $(T_c - T_a)$ and VPD, which makes it difficult to apply this method in practice. Jalali-Farahani et al. (1993) found that the theoretical CWSI was the most promising approach for scheduling irrigation for Bermudagrass turf, compared with the empirical CWSI of Idso et al. (1981) and with an empirical model that included net radiation as an independent variable. Because of the difficulty of using the theoretical CWSI, however, most researchers have preferred to use the empirical approach of Idso et al. (1981), which has been shown to work relatively well for a given location as long as locally calibrated baselines are available (Yazar et al., 1999; Irmak et al., 2000). To establish the lower and upper baselines, however, most researchers have only included VPD and $(T_c - T_a)$ and have assumed that other factors affecting $(T_c - T_a)$, such as available energy and wind speed, are constant if measurements are made close to noon and under clear-sky conditions.

This assumption, however, is problematic because it is well known that both the available energy and wind speed change, among other things, with location, time of day, and day of the year. Because of this, empirical baselines for the same crop will be different under different solar radiation and wind speed conditions, as suggested by Zolnier et al. (2001), Jensen et al. (1990), and Al-Faraj et al. (2000). Figure 1 shows the different lower (non-water-stressed) near-noon baselines that researchers have used for corn and alfalfa. It shows that the non-water-stressed baseline for a particular crop can be considerably different for different locations.

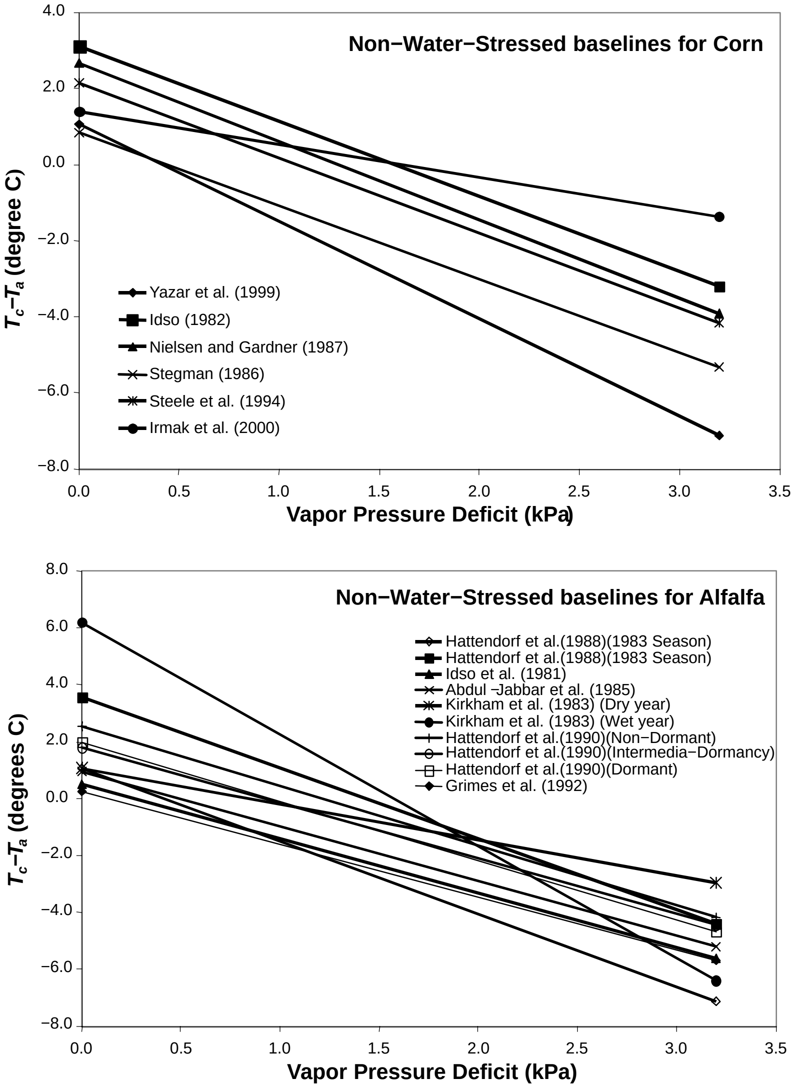


Figure 1. Non-water-stressed near-noon baselines reported by several researchers for corn and alfalfa.

The same type of disagreement is found in defining the upper baseline. For instance, for corn, Shanahan and Nielsen (1987) and Nielsen and Gardner (1987) used a maximum value of $(T_c - T_a) = 3^\circ$C as the upper baseline. Steele et al. (1994), however, used 5°C, and Irmak et al. (2000) used an average value of 4.6°C. Sadler et al. (2000), however, reported values of $(T_c - T_a) > 10^\circ$C, and Jensen et al. (1990) found $(T_c - T_a)$ values for several crops as high as 8°C for high levels of solar radiation and $(T_c - T_a)$ values approaching zero or even negative at low levels of solar radiation.

The lack of transferability of the baselines, together with the restriction of having to make required measurements close to noon and under clear-sky conditions, are major drawbacks of using the empirical CWSI for irrigation scheduling. An attempt to develop transferable baselines have recently been made by Alves and Pereira (2000), who provided a new definition of the non-water-stressed baseline based on the difference between the canopy temperature and the wet bulb temperature of air, instead of the air temperature. This new concept, however, requires almost as much information as the theoretical approach of Jackson et al. (1981). The objectives of this study were to: (1) evaluate the effect of solar radiation on the non-water-stressed baseline of alfalfa and tall fescue grass, and (2) develop empirical equations to estimate the non-water-stressed baselines for these two crops, which could be applied at any time during the daytime cycle and under conditions of full canopy cover.

METHODS

Data included in this study were collected as part of a larger study from a tall fescue grass and an alfalfa field at Kimberly, Idaho, from June to October of 1991 (Payero et al., 2003, 2004, 2005). The tall fescue grass was clipped every week to a height of approximately 0.09 m. The fields were located within a large, nearly flat, irrigated area, which was affected by regional advection. The soil at the research site was a Portneuf silt loam. Both fields were fully irrigated to meet crop water requirements, based on calculated daily evapotranspiration data. The alfalfa field was wetted five times during the study, either by heavy rain or irrigation, while the tall fescue grass field was wetted eight times. Neither crop showed signs of being under water stress at any time during the study. Soil moisture from a depth of 0 to 0.10 m was measured from each field approximately every three days using the gravimetric method. Irrigation was applied using a gated-pipe surface irrigation system.

Meteorological data for this study were collected using a Bowen ratio system (model 023A, Campbell Scientific, Inc., Logan, Utah), which was described in detail by Tanner et al. (1987). This system measured dew point and air temperature at two heights above the crop canopy, as well as net radiation (R_n) and soil heat flux (G) needed to close the one-dimensional energy balance equation. Air temperature was measured using fine-wire chromel-constantan thermocouples (76 μm), which were installed at the far end of two arms. These arms were installed extending towards the south, approximately 1.5 m from a central tower. The two arms were at different heights above the canopy and within the surface boundary layer. Dew point was measured from air samples drawn alternately from each arm using a vacuum pump. Air drawn from a given height first passed through a mixing plastic container and then was drawn through a thermoelectric cooler. The thermoelectric cooler housed a cooled-mirror hygrometer (model Dew-10, General Eastern Corp., Watertown, Mass.), which measured the dew point. The process was then repeated using air drawn from the other arm. The average from both arms of the measured dew points and air temperatures were used to calculate the actual vapor pressure (e_a) and the saturation vapor pressure (e_s) of the air, respectively, using equations in EWRI (2001), originally proposed by Tetens (1930). These values were then used to calculate the vapor pressure deficit (VPD) of the air.

In addition to the measurements required for the application of the Bowen ratio method, measurements relevant to this study included wind speed, solar radiation, and radiometric surface temperature (T_c). Solar radiation was measured using an Eppley pyranometer (The Eppley Laboratory, Inc., Newport, R.I.). Wind speed was measured using a 3-cup anemometer (model 12102D, R.M. Young Co., Traverse City, Mich.). The anemometer was placed at a height of 1.86 m over the alfalfa field and 1.83 m over the tall fescue grass field. Wind speeds were transformed to the standard 2 m height using the equation by Allen et al. (1989). Radiometric surface temperature was measured using two infrared thermometers with a 15° field of view (model 4000A, Everest Interscience, Inc., Tucson, Ariz.). Air temperature and dew point were measured every second, and all other variables every 10 s, using a 21X micrologger (Campbell Scientific, Inc., Logan, Utah), which averaged and stored data every 20 min.

The infrared thermometers were wrapped with white-painted tinfoil to minimize changes in sensor body temperature, which can result in errors in the temperature measurements. Before installing the infrared thermometers in the field, they were first calibrated using a black body calibration source. There was a good linear relationship between the temperature of the black body and that measured by each of the infrared thermometers, resulting in $r^2 > 0.99$, but with some departure from the 1:1 line. The readings from each sensor were then adjusted to match the temperature of the black body using calibration equations derived for each sensor. Once installed in the field, the outputs from the infrared thermometers were further multiplied by 0.98 to correct for emissivity of the crop canopies, which differs from the value of 1.0 assumed for the black body. The infrared thermometers were installed in the field at a height of approximately 1 m above the crop canopy, and at a 45° angle from horizontal, with one of the sensors looking east and the other looking west. The instruments looked at a target of approximately 0.73 m in diameter. The average of the radiometric surface temperatures measured by the two thermometers was used in the analysis.

To avoid confounding the canopy temperature measurements with the influence of the soil background, this study only presents data collected during periods when the soil surface was not exposed. For alfalfa, for instance, only data collected after the crop reached a height of 0.4 m were included in this study. Twenty plant canopy height measurements were taken from each field approximately every other day to calculate the average plant canopy height for each crop.

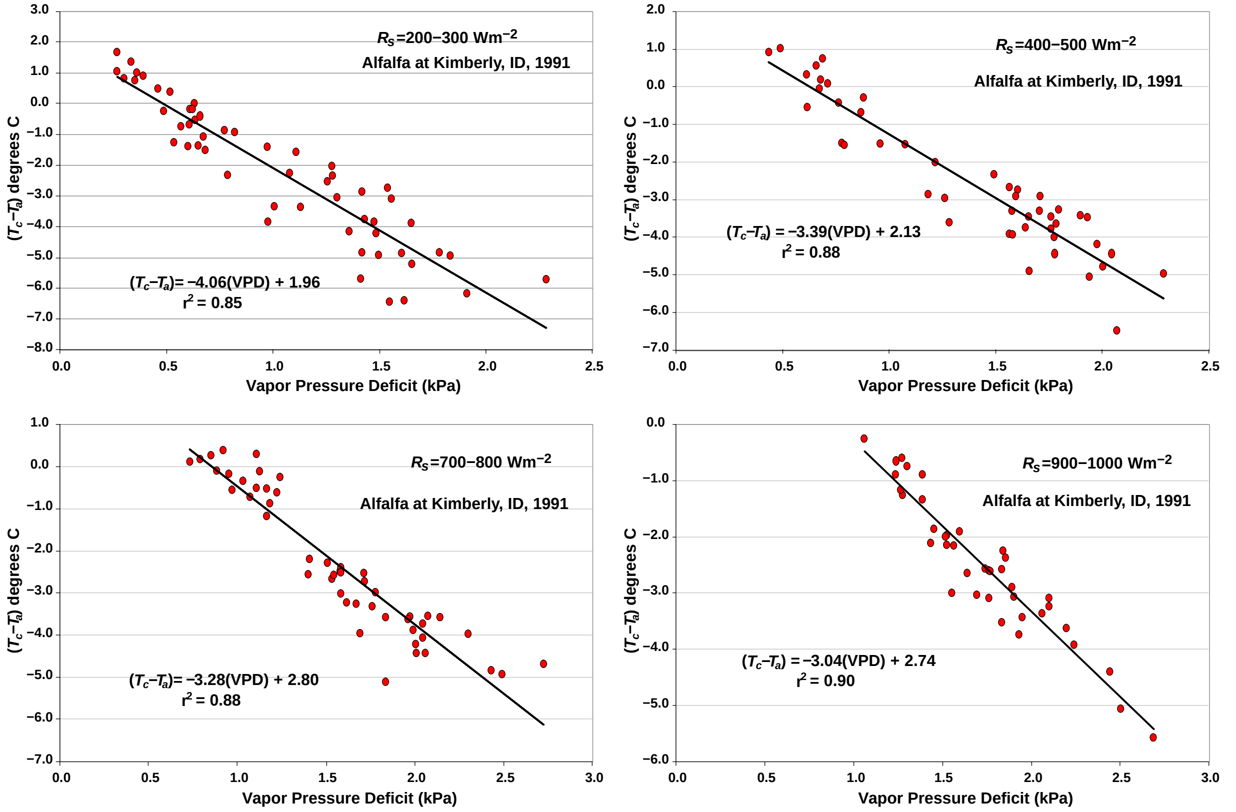


Figure 2. Non-water-stressed baselines for different solar radiation levels for alfalfa, obtained at Kimberly, Idaho, in 1991. Each point represents a 20 min average collected at different times during the study period.

RESULTS AND DISCUSSION

EFFECT OF SOLAR RADIATION

The first objective of this study was to evaluate the effect of solar radiation (R_S) on the non-water-stressed baseline of alfalfa and tall fescue grass. To evaluate this effect, the 20 min data for the entire study period for each crop were divided into 100 W m^{-2} R_S increments. Linear regression analysis was then used to develop the baselines for each 100 W m^{-2} R_S increment. Figure 2 shows that using this procedure for alfalfa, it was possible to define relatively good linear relationships for most R_S increments.

Results of the linear regression analysis for both crops (table 1) also indicate that similar results were obtained for grass. The linear relationship was statistically significant in all cases ($P < 0.01$). These relationships resulted in $r^2 > 0.80$ in most cases and in $r^2 \geq 0.90$ for a couple of R_S ranges. Table 1, however, shows poor correlation during nighttime (when $R_S = 0$ W m^{-2}) and when R_S was in the range of 0 to 100 W m^{-2}. These results may be due to the fact that during nighttime, energy sources that could influence canopy temperature are mainly supplied by the soil surface (soil heat flux), net radiation, and by advective heat carried by wind. The 0 to 100 W m^{-2} R_S range, on the other hand, usually occurs during early morning and late afternoon (assuming clear-sky conditions), at times when the solar energy hits the surface at very low solar altitude angles. Under these conditions, surface albedo is high (Dong et al., 1992) and a large portion of R_S is consequently reflected from the surface, having a reduced impact on the energy balance of the surface.

The fact that different baselines can be developed for different R_S ranges explains why different researchers at

Table 1. Results of regression analysis to estimate ($T_c - T_a$) (°C) from vapor pressure deficit (kPa) for every 100 W m^{-2} solar radiation (R_s) increment for non-water-stressed alfalfa and tall fescue grass at Kimberly, Idaho. Analysis included 20 min averages. For alfalfa, only data collected when alfalfa canopy height was greater than 0.40 m were included (*n* = number of data pairs used in the analysis, SEE = standard error of estimate).

R_S Range (W m^{-2})	Slope	Intercept	r^2	*n*	SEE (°C)
Alfalfa					
0	−1.31	0.23	0.30	380	0.78
0-100	−1.56	−0.67	0.18	140	1.67
100-200	−4.41	1.88	0.82	86	0.97
200-300	−4.06	1.96	0.85	54	0.87
300-400	−3.42	1.87	0.80	59	0.86
400-500	−3.39	2.13	0.88	46	0.67
500-600	−3.42	2.58	0.88	51	0.64
600-700	−3.49	2.83	0.88	48	0.68
700-800	−3.28	2.80	0.88	49	0.59
800-900	−3.14	2.94	0.80	119	0.66
900-1000	−3.04	2.74	0.90	39	0.39
Grass					
0	−3.30	−0.34	0.64	465	0.97
0-100	−3.49	−0.23	0.37	137	2.02
100-200	−4.58	2.15	0.82	59	1.02
200-300	−4.41	3.22	0.91	49	0.72
300-400	−3.02	2.71	0.87	45	0.78
400-500	−3.08	3.21	0.86	50	0.75
500-600	−3.07	4.28	0.85	56	0.79
600-700	−2.57	4.32	0.81	71	0.84
700-800	−2.40	4.68	0.81	67	0.76
800-900	−2.33	5.32	0.65	128	0.99
900-1000	−2.07	5.32	0.58	14	0.91

different locations have used different baselines, as previously illustrated in figure 1. A plot of all the observed non-water-stressed baselines for each 100 W m^{-2} R_s increment for alfalfa and grass (fig. 3) shows that the baselines tended to converge as vapor pressure deficit (VPD) decreased.

The baselines converged at values of approximately 2°C to 3°C and 2°C to 5°C when VPD = 0 kPa for alfalfa and grass, respectively. As the VPD increased, on the other hand, the baselines departed from each other. The departure, however, was more pronounced for grass than for alfalfa. For alfalfa, for instance, when VPD = 3.0 kPa, the baselines ranged from approximately −6.5°C to −11.5°C. For grass, a wider range (from −1°C to −11.5°C) was observed. These results indicate that for grass, the baselines were more sensitive to changes in solar radiation than they were for alfalfa. It also shows that R_s can significantly affect the baseline, and that the effect of R_s is more pronounced as the VPD increases, that is, as the air gets dryer. Therefore, considering the effect of R_s on the baseline would be more important in arid areas than it would be in humid areas. Jalali-Farahani et al. (1993) showed lower baselines for different levels of net radiation (R_n) for Bermudagrass turf that were parallel to each other, instead of the diverging lines found in this study. The results of this study, however, are similar to those reported by Jalali-Farahani et al. (1993) in the sense that they also found that the baselines changed with R_n. Although in this study we used R_s instead of R_n, the comparison between the two studies is still valid since there is usually a good linear correlation between these two variables for a given surface.

Effect of Other Variables

Figure 2 and table 1 show that even though relatively good linear relationships were obtained for the daytime non-water-stress baselines, the relationships still showed some scatter. The scatter could be due to other factors, in addition to R_s and VPD, such as wind speed (u_2), air temperature (T_a), soil moisture (θ_v), and plant canopy height (h). Canopy height could have an effect since it affects the zero plane displacement and roughness length that, together with wind speed, influence the aerodynamic resistance of the surface. Although soil moisture is known to affect ($T_c - T_a$) (Al-Faraj et al., 2000), in this study both crops were well irrigated during

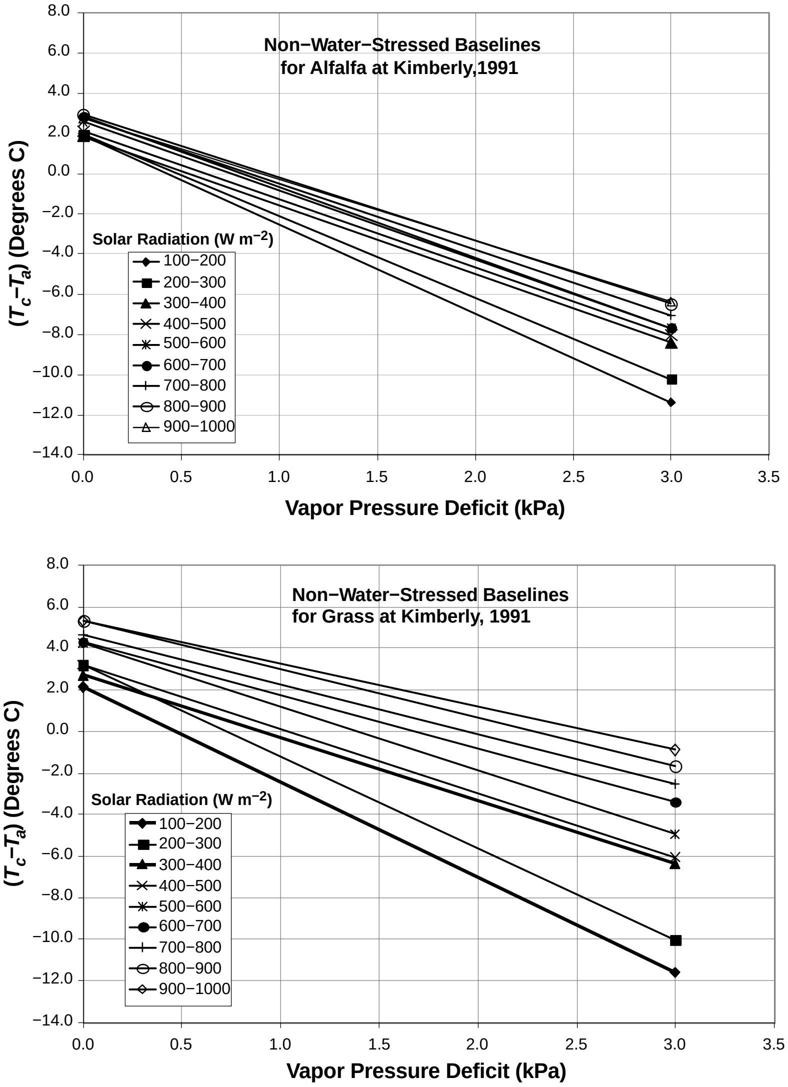


Figure 3. Non-water-stressed baselines for alfalfa and tall fescue grass for every 100 W m^{-2} solar radiation increment. The lines were plotted using equations developed from the data in table 1.

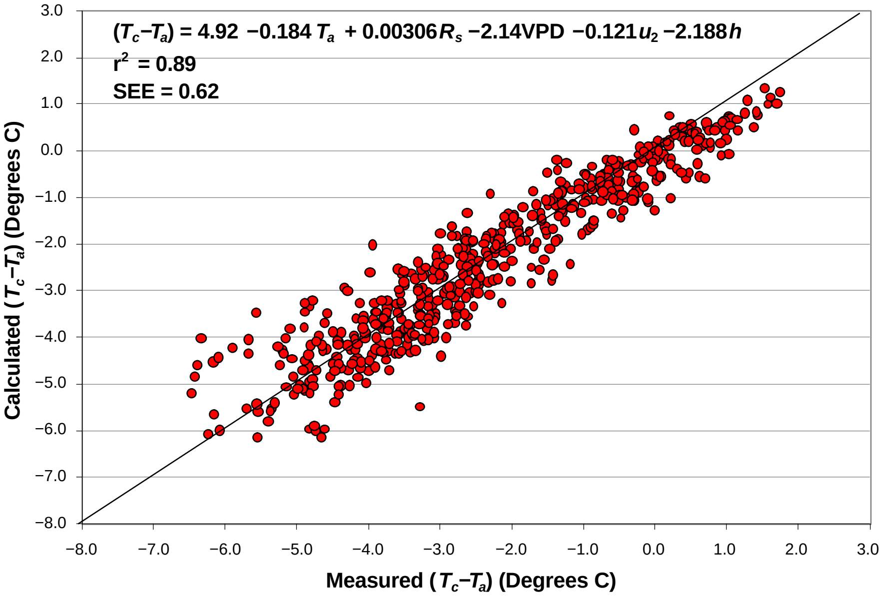


Figure 4. Performance of multiple regression model to estimate daytime ($T_c - T_a$) as a function of vapor pressure deficit (VPD), solar radiation (R_s), air temperature (T_a), wind speed (u_2), and plant canopy height (h) for non-water-stressed alfalfa at Kimberly, Idaho. Each point represents a 20 min average collected during DOY 197 to 213 (h = 0.4 to 0.75m).

the data collection period and therefore θ_v was not expected to have a significant effect under these conditions.

Multiple linear regression analysis was used to develop a single equation to estimate the daytime non-water-stress baseline (NWSB) for each crop. The analysis used 20 min data for the entire study period, including all variables that could significantly affect ($T_c - T_a$), and that farmers could measure on site using commonly available instrumentation. These variables included VPD, R_s, T_a, u_2, θ_v, and h. For alfalfa, the analysis only included data when h was higher than 0.4 m to ensure full canopy cover. All of the variables included in the model, except for soil moisture (θ_v), were statistically significant ($P < 0.01$). Therefore, by including all these variables, it was possible to obtain a single equation to estimate the NWSB for alfalfa (fig. 4). This equation could be applied at any time during the daytime hours (especially when $R_s > 100$ W m^{-2}) and during the part of the growing cycle with full canopy cover. This equation resulted in a relatively high r^2 of 0.89, and the comparison between the measured and calculated ($T_c - T_a$) values (fig. 4) shows that the calculated values followed the 1:1 line, which indicates good agreement with the measured values.

Results of the analysis for tall fescue grass (fig. 5), however, show that plant canopy height was not statistically significant, which can be explained by the limited range of plant canopy heights included in the analysis (0.10 to

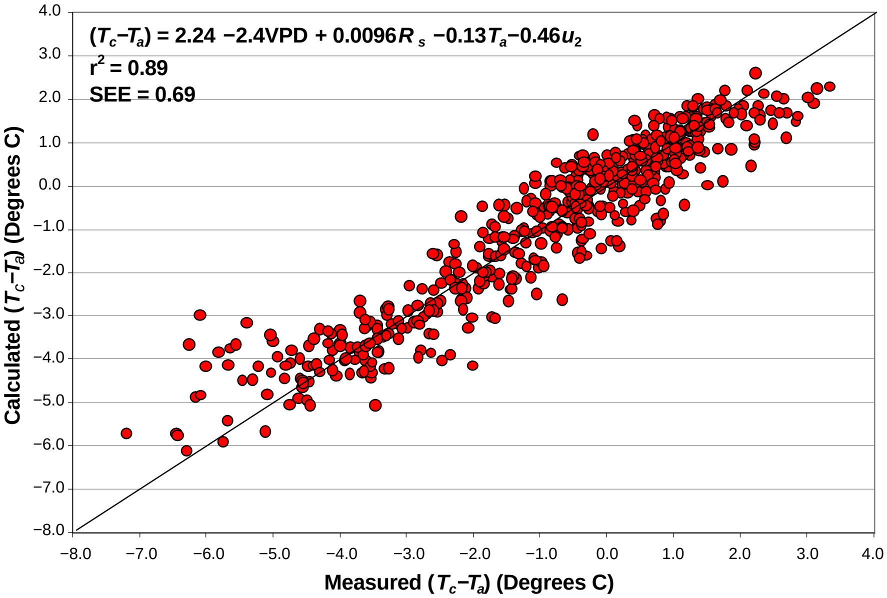


Figure 5. Results of multiple linear regression analysis to estimate ($T_c - T_a$) for non-water-stressed tall fescue grass as a function of vapor pressure deficit (VPD), solar radiation (R_s), air temperature (T_a), and wind speed (u_2). Analysis included 539 20−min averages collected during daytime from DOY 213 to 231 at Kimberly, Idaho.

Table 2. Results of multiple linear regression analysis to estimate ($T_c - T_a$) for non-water-stressed alfalfa and tall fescue grass near noon as a function of vapor pressure deficit (VPD), solar radiation (R_s), air temperature (T_a), wind speed (u_2), plant canopy height (h), and soil moisture (θ_v). Analysis included observations collected every 20 min near noon (11:00-14:00 h) from DOY 197 to 213 (h = 0.4 to 0.75 m) for alfalfa and from DOY 213-231 for grass at Kimberly, Idaho.

Variable	Data Range	Coefficient
Alfalfa		
Intercept		5.520
T_a (°C)	20-32	−0.208
R_s (W m^{-2})	200-1000	0.0032
VPD (kPa)	0.5-2.8	−2.148
u_2 (m s^{-1})	0.4-5.0	−0.430
h (m)	0.4-0.75	−1.521
θ_v (m^3 m^{-3})	0.15-0.34	--
r^2	0.92	
SEE (°C)	0.42	
n	145	
Grass		
Intercept		1.639
T_a (°C)	21-34	--
R_s (W m^{-2})	290-1000	0.009
VPD (kPa)	1.25-3.50	−3.181
u_2 (m s^{-1})	0.8-5.2	−0.825
h (m)	0.10-0.19	--
θ_v (m^3 m^{-3})	0.18-0.34	--
r^2	0.94	
SEE (°C)	0.43	
n	152	

0.19 m). The relationship for tall fescue grass resulted in the same r^2 of 0.89 as for alfalfa, which is much better than the r^2 = 0.76 reported by Jalali-Farahani et al. (1993 and 1994) using only VPD as the independent variable. The calculated ($T_c - T_a$) values using the derived equation for tall fescue grass also followed the 1:1 line as compared with the measured values (fig. 5).

Although the equations derived for alfalfa and grass resulted in good correlation, some scatter is still observed in figures 4 and 5. The scatter could be due to the fact that other factors, not included in the analysis, like soil heat flux (G) and albedo (α), could affect the energy balance of the plant canopy and could, therefore, influence ($T_c - T_a$). These factors were not included in the analysis because they are difficult to obtain since they are not commonly measured. However, it is recognized that they change during the day and during the growing season (Payero et al., 2003; Dong et al., 1992) and could affect ($T_c - T_a$).

Since many remote sensing applications commonly collect data near noon (Jiang and Islam, 2001), the previous multiple regression analysis was also conducted including only the subset of data collected near noon, i.e., including only the 20 min data collected between 11:00 and 14:00 hours for both crops. Data included an ample range of values for all meteorological variables, as shown in the “Data Range” column in table 2. For instance, R_s values in the range of 200 to 1000 W m^{-2} and wind speeds between 0.40 to 5.2 m s^{-1} were included in the near-noon analysis.

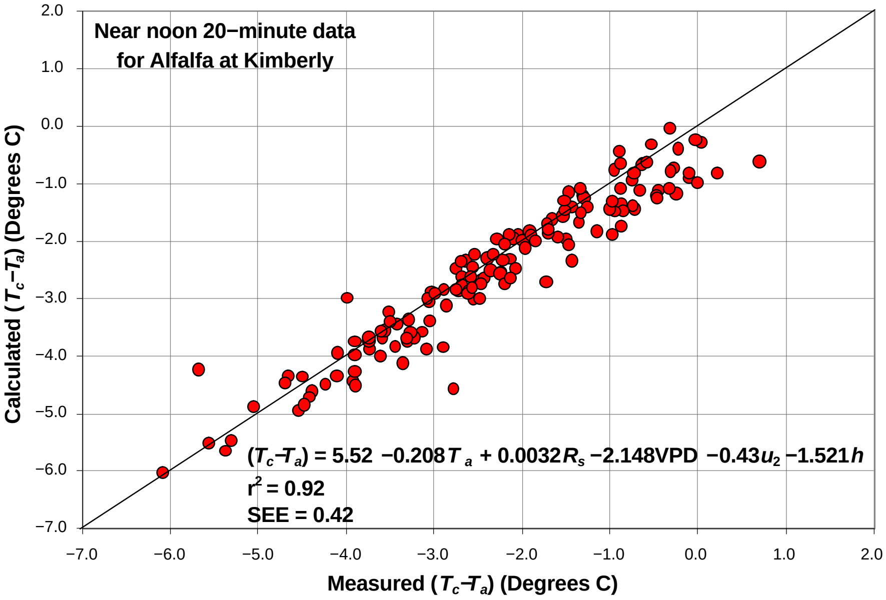
For alfalfa, all variables included in the analysis were statistically significant, except for soil moisture. For grass, on the other hand, air temperature (T_a), plant canopy height (h), and soil moisture were not statistically significant. For alfalfa, the near-noon multiple regression model resulted in r^2 = 0.92 and for grass, r^2 = 0.94. For alfalfa, the multiple regression model included air temperature (T_a), solar radiation (R_s), vapor pressure deficit (VPD), wind speed (u_2), and plant canopy height (h). For grass, on the other hand, the model only included VPD, R_s, and u_2. Comparison of measured ($T_c - T_a$) data to the values calculated with the near-noon models for both crops (fig. 6) indicates that, in addition to being highly correlated, the calculated values followed the 1:1 line with respect to the measured values. These results point out that even when data are only collected near noon, as is common in remote sensing applications, the NWSBs should be defined including all the variables that significantly influence ($T_c - T_a$).

The approach used in this study to develop the equations to estimate the NWSBs could also be used to develop the water-stressed baselines needed to calculate the CWSI. It could also be used to develop a model that includes soil moisture as an independent variable, which could then be applied for irrigation scheduling. For instance, Geiser et al. (1982) developed a multiple regression model to estimate ($T_c - T_a$) from net radiation, available water, and relative humidity for corn and then used the model for irrigation scheduling. Using the developed model for scheduling irrigation for corn, they were able to use 39% and 18% less water without significant yield loss compared with scheduling irrigation using a water balance method and using resistance blocks, respectively. The results of this study could also be used for irrigation system automation using canopy temperature measurements, and could have applications for detecting well-watered pixels using remote sensing.

CONCLUSION

The results of this study demonstrate that by using multiple regression analysis, it is possible to develop non-water-stressed CWSI baselines for specific crops with full canopy cover. These results also confirm that under non-water-stressed conditions, ($T_c - T_a$) is a function of climate and crop variables, as has been previously proposed by the theoretical approach of Jackson et al. (1981) and Jackson (1982). One problem not addressed in this study, but still in need of attention, is the development of a model to estimate the NWSBs for incomplete canopies.

Since in this study we took into account the variables that significantly affected the NWSBs, we expect that the proposed equations to estimate the NWSBs will be transferable to other locations, as long as the crops and cultivars are the same as the ones used in this study. However, since these equations were developed from a dataset collected at only one location, researchers and practitioners are encouraged to test them in other environments. The fact that the equations developed in this study can be used any time during the daytime hours, except for those developed specifically for the near-noon period, is an improvement over the commonly used method proposed by Idso et al. (1981), which requires measurements to be made close to noon. Even when measurements are made close to noon, the equations developed in this study for the near-noon period take into account changes in weather variables, which should make them consistent from one location to another.



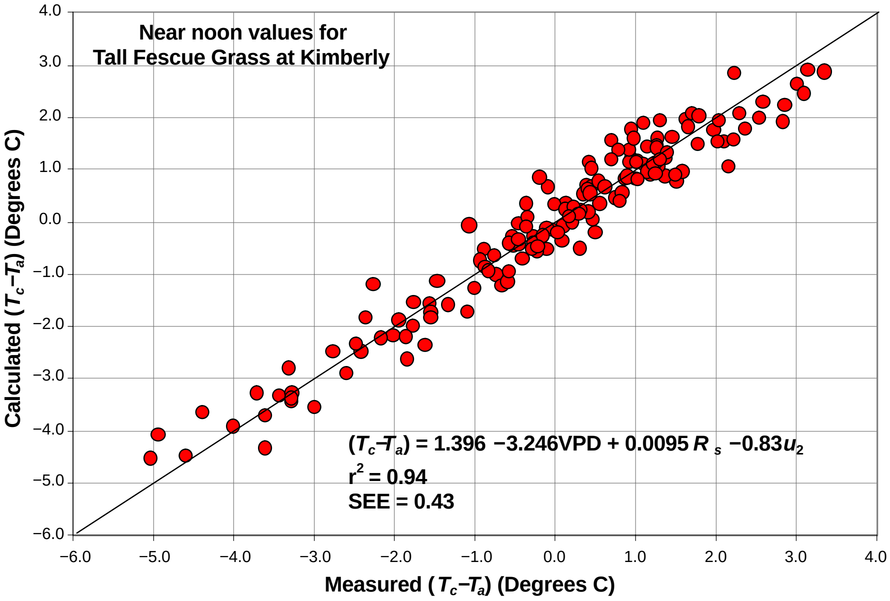


Figure 6. Comparison of ($T_c - T_a$) values measured and calculated near noon. Values of ($T_c - T_a$) were calculated using multiple regression models that estimate ($T_c - T_a$) as a function of vapor pressure deficit (VPD), solar radiation (R_s), air temperature (T_a), wind speed (u_2), and plant canopy height (h) for non-water-stressed alfalfa and grass at Kimberly, Idaho. Each measured value represents a 20 min average collected near noon (11:00-14:00 h) during DOY 197 to 213 (h = 0.4 to 0.75m) for alfalfa and during DOY 213 to 231 for grass.

ACKNOWLEDGEMENTS

This project was supported by the Utah Agricultural Experiment Station, The University of Nebraska Agricultural Research Division, the Remote Sensing Services Laboratory at Utah State University, The Instituto Superior de Agricultura, The Organization of American States, The Latin American Scholarship Program for American Universities, and USDA−ARS.

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