PRECISION IRRIGATION MANAGEMENT USING MODELING AND REMOTE SENSING APPROACHES.[**]

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ABSTRACT

A synergy between remote sensing and crop simulation models is proposed as a new method for managing irrigations in precision agriculture. The remote sensing component provides the ability to assess plant water status at high spatial resolution and the crop model provides data at high temporal frequency. The objective of this study was to integrate the crop water stress index (CWSI) and the simulation model CERES-Wheat to provide data on within-field variability in plant water requirements and yield response. The accuracy of the procedure was evaluated using a data set collected during the Free Air Carbon Dioxide Enhancement (FACE) wheat experiments conducted at the Maricopa Agricultural Center in Arizona. The method was very sensitive to overestimation of the CWSI under dry conditions with a potential for inaccurately predicted soil water contents. However, the combined approach allowed the model to provide reasonable yield prediction of water stressed plots using only CWSI measurements during the season to indicate inadequate plant available water. These initial results are encouraging; however, additional analysis of the data on a plot-by-plot basis is necessary before specific conclusions can be made about the suitability of this method for precision farming applications.
KEYWORDS: Crop simulation modeling, Crop water stress index, Precision farming

INTRODUCTION

The management of spatial variability in plant-extractable water content is difficult, because measurements of soil water content are not practical at a high spatial density. A high spatial resolution soil map can be used with a water balance or crop simulation model to provide some estimate of the variability in soil water; however, it is difficult to quantify all of the information that could impact the water status in a particular area of the field to insure the model's accuracy (i.e., irrigation uniformity, undocumented differences in soil properties, rooting depth, etc). Thermal imagery from an aircraft or satellite can be used to determine crop water status at a high spatial resolution (e.g. Moran, 1994), but this approach requires frequent image acquisitions and is subject to cloud interference. The integration of these two technologies has been found to be an effective method to improve yield prediction in a number of studies as reviewed by Moulin et al. (1998). Specifically applied to agricultural water management, Moran (1994) discussed a scenario in which a model and Landsat imagery could be used in a cost-effective manner for irrigation scheduling if the producers within an irrigation district were to share the cost of imagery. The objective of this study was to extend the approach of Moran (1994) to address

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field level variability using the crop simulation model CERES-Wheat and the crop water stress index (CWSI) to adjust the model's prediction of soil water content. The results presented in this paper are limited to initial trials to assess the feasibility of the proposed model and CWSI integration method.

MATERIALS AND METHODS

Evaluation Data Set

The modifications made to the model were evaluated using a wheat growth data set collected during the wheat Free Air Carbon Dioxide Enrichment (FACE) experiments conducted in Maricopa, Arizona. Kimball et al. (1995) and Hunsaker et al. (1996) provide details of the experimental procedures and setup. Two seasons of growth data were used in the evaluation. In each year a hard red spring semi-dwarf wheat (*Triticum aestivum* L. cv. Yecora Rojo) was planted at a 0.25 m row spacing. In both seasons there were Wet and Dry irrigation treatments under both enriched and ambient CO_2 levels. In the 1992-93 season, the irrigation timing was the same for both treatments until 31 January. After this time the Wet treatments received two irrigations on 1 March (13 mm) and 9 March (60 mm) that were not applied to the Dry treatments. Beginning on 18 March, both treatments were irrigated on the same days, but the Dry treatments received half of the water applied to the Wet treatments (season totals: 602 mm Wet, 275 mm Dry, excluding an early-season irrigation of 317 mm applied to both treatments). In the 1993-94 season, the Dry treatments were irrigated with the same amount per irrigation, but at half the frequency of the Wet treatments (season totals: 629 mm Wet, 287 mm Dry). Irrigation water was applied through a sub-surface drip system (0.5 m tube spacing, 0.3 m emitter spacing, 0.2 m depth). Although the CERES model does have the ability to simulate plant response to elevated CO_2 levels, the focus of this evaluation was only on the irrigation treatments. Destructive plant sampling from each of the treatments began each season soon after emergence and continued through crop maturity. Neutron readings were taken to a depth of 2.1 m at 20 cm intervals during both seasons to determine soil moisture content with the exception of the first 10 cm where TDR readings were used. These data were used to estimate average evapotranspiration rates as described by Hunsaker et al. (1996).

Infrared Thermometer Readings and CWSI Calculation

Hand-held infrared thermometer (IRT, Everest Model 110, 15-degree field of view) readings during or shortly after solar noon were made at regular intervals in each of the plots during the growing season. Six readings were taken while walking to the north with the IRT pointed in an oblique angle (~ 45° from horizontal) to the north. Six additional readings were taken while walking to the south. In this analysis, all of the oblique IRT readings of each plot were averaged to obtain a single canopy temperature per treatment replicate per day. At the beginning and end of each measurement period, wet and dry bulb temperatures were measured with a hand-held psychrometer. These measurements were used to calculate a vapor pressure deficit. IRT readings were also taken of a black body to confirm the IRT's calibration. Only data from days with no cloud interference to the solar beam were selected. Data collected when the green leaf area index was less than 3.0 were not used, as soil background in the field of view of the IRT could lead to false indications of water stress. Additionally, readings taken on the day of or one day after irrigation were not used, as plant response to irrigation can be delayed near the time of water application. In the 1992-93 season, of the 63 IRT data sets available, 25 met the previous criteria and only 8 of 59 in 1993-94.

The CWSI was calculated using the form presented by Idso (1982):

$$\text{CWSI} = [(T_c - T_a) - dT_l] / (dT_u - dT_l) \tag{1}$$

where T_c is the average canopy temperature (°C), T_a is air temperature (°C, average of the air temperatures at the start and end of IRT measurements), dT_l is the canopy-air temperature difference of a well-watered crop (lower limit, °C), and dT_u is the canopy-air temperature difference of a completely water stressed crop (upper limit, °C). The upper and lower limits were calculated as

$$dT_l = I_c + S_c\,\text{VPD} \tag{2}$$

$$dT_u = I_c + S_c\,(VP_o\{T_a\} - VP_o\{T_a + I_c\}) \tag{3}$$

where I_c (°C) and S_c (°C kPa^{-1}) are the intercept and slope of a crop specific non-water-stressed baseline respectively, VPD is vapor pressure deficit (kPa) and $VP_o\ \{x\}$ is saturated vapor pressure at temperature x (kPa). The intercept and slope values used in this study for wheat were taken from Idso (1982): $I_c = 3.38$, $S_c = -3.25$, pre-heading; $I_c = 2.88$, $S_c = -2.11$, post-heading. For the time from the beginning of head formation to dough fill, a time-weighted average of the previous parameters was used. To investigate the sensitivity of the model to potential errors in the CWSI, a CWSI was also determined by calculating the lower limit as the canopy air-temperature difference in the Wet irrigation treatments.

Model Description

CERES-Wheat (Ritchie and Otter, 1985) was selected for use because it is a process oriented model capable of simulating different management practices while maintaining reasonable input requirements that would not prevent its application by a farm manager. Additionally, the model has been integrated as part of the Decision Support System for Agrotechnology Transfer (DSSAT, Hoogenboom et al., 1994), providing several tools with which to manipulate the model's output for use in decision making. The model is capable of simulating plant response to weather conditions, and to soil-moisture and nitrogen availability. The model's prediction of crop phasic development is controlled primarily by a growing-degree day approach. Additional model details relevant to the modifications made to the model are presented in the following discussion.

The version of CERES-Wheat used is distributed with DSSAT version 3.5, with code obtained from Gerrit Hoogenboom (Professor, University of Georgia, Tifton). A different version of the CERES model was evaluated for this data set by Tubiello et al. (1999). The model requires variety specific parameters, and those determined by Tubiello et al. (1999) were used with two exceptions: the leaf area to weight ratio was decreased from 300 to 200 cm^2 g^{-1} and the kernel number per unit stem weight was reduced from 34.5 to 29 g^{-1} based on predictions of the Wet treatment in the 1992-93 growing season. The need for these adjustments is due to changes in CERES since the work of Tubiello et al. (1999).

The model predicts transpiration as a function of either the plant available water in the root zone or atmospheric limitations (potential transpiration, E_p), whichever is smaller. The potential water uptake by the roots (RWU_L, cm^3 water per cm roots per day) in a particular soil layer (L) is calculated by

$$RWU_L = c_1 \exp[c_2 (SW_L - LL_L)] / [c_3 - \ln(RLV_L)] \quad (4)$$

where c_x are empirical constants, SW_L is the soil water content ($cm^3\ cm^{-3}$), LL_L is the soil water content at permanent wilting point ($cm^3\ cm^{-3}$) and RLV_L is the root length density (cm root per cm^3 of soil). The model calculates the equivalent depth of water withdrawn from each soil layer (RWU_L * RLV_L * [Layer Thickness, cm]) and sums the potential water uptake in each layer to determine "root" potential transpiration ($TRWU_p$, cm). If $TRWU_p$ is greater than potential transpiration for the day, RWU_L is decreased so that the water uptake by the plant is equal to potential transpiration. Otherwise, if the sum of RWU_L across the soil profile is less than potential, transpiration is set equal to $TRWU_p$. A crop water stress factor is then defined as

$$SWDF1 = TRWU_a / E_p \quad (5)$$

where $TRWU_a$ is actual total root water uptake (cm) and E_p is potential transpiration (cm).

As SWDF1 is essentially equivalent to the definition of (1-CWSI), the model was modified so that if there was a CWSI observation on a given the day and (1-CWSI) was not within 10 percent of SWDF1, $TRWU_a$ was calculated as

$$TRWU_a = (1\text{-}CWSI)\ E_p \quad (6)$$

The root water uptake in each layer was then adjusted by

$$RWU_L = [E_p\ (1\text{- }CWSI) / TRWU_a]\ RWU_L \quad (7)$$

Next, the soil water content was recalculated as a function of RWU_L by solving Eq. (4) for SW_L. This technique assumes that the relative root and soil water distributions do not change. A major limitation to this approach is evident when the model is predicting water stress when in reality, there is more than adequate water available to the roots. It is only possible to adjust the soil water profile back to a condition where the model is on the verge of predicting water stress. That is, if the CWSI is 0, there is no way to infer how much water should be added to the profile beyond what is needed to prevent a prediction of water stress on the day the CWSI was taken. Therefore, this approach will not perform well when the model is severely under-estimating plant available water.

Simulations

To investigate the accuracy of this approach, four basic simulations were conducted using CWSI observations from the ambient CO_2 treatments:

1. Simulate the Dry irrigation treatment and input all of the CWSI measurements available using a calculated lower limit (i.e., dT_l determined from Eq. (2), **D_iD_a**).
2. Simulate the Dry irrigation treatment and input all of the CWSI measurements available using the measured canopy temperature in the Wet treatments to determine a lower limit (**D_iD_w**).
3. Simulate the Wet irrigation treatment and input all of the CWSI observations for the Dry treatments (**W_iD_a**).
4. Simulate the Wet irrigation treatment and input eight CWSI observations at roughly 10 day intervals (**D_iD_8**).

Simulation sets 1 and 2 were conducted to investigate the possible sensitivity of the method to errors in the CWSI lower limit, assuming the CWSI calculated using the control Wet canopy temperatures for the lower limit represents the "true" CWSI. Simulations 3 and 4 were executed to determine the ability of the method to correct for conditions where soil water content is severely over estimated by the model.

RESULTS

Model Results Without CWSI Modification

Table 1 is a summary of the model's predictions of growth stage, dry matter production, and evapotranspiration (ET) for the Wet and Dry treatments for both growing seasons. In the 1992-93 season the model-predicted anthesis date is 10 days later than observed, but the model was closer in its prediction of maturity. The model does not account for the differences in growth stage due to water stress, as transition between growth stages is primarily a function of growing degree-days. The end of season dry matter predictions (both above ground and grain yield) were in close agreement to those observed in both seasons for the Wet treatments; however, the model tended to under predict above-ground dry matter in the Dry treatments. These results are similar to those obtained by Tubiello et al. (1999) with the exception of predicted evapotranspiration (ET). Tubellio et al. found that the model under-predicted ET for the Wet treatments by 90 to 100 mm. However, Tubiello et al.'s version of the model used the Priestley-Taylor equation to determine potential ET. In this study, the FAO Penman equation was used for potential ET. Results similar to Tubiello et al.'s were obtained using the Priestley-Taylor equation.

Model Results with CWSI Inputs

The use of the Dry CWSI observations when simulating the Dry treatments did not have a significant impact on the models predictions of dry matter of ET (Table 2). The addition of the CWSI observations slightly improved total dry matter prediction, but decreased the accuracy of yield prediction in both years. After heading, the CWSI indicated a higher level of stress than predicted by the model alone and thus reduced the predicted level of plant available water (PAW), resulting in the decreased yields. As the model's prediction of PAW was in good agreement with those obtained from the neutron readings, this could indicate that the parameters used to determine the CWSI during post heading are not appropriate for this variety of wheat.

Additionally, in the 1993-94 season, the model over-predicted green leaf area (GLA) later in the season (data not shown). GLA is used by the model to determine E_p, and over-prediction of E_p would also result in the CWSI adjustment procedure removing too much water from the profile.

Table 1. Comparison between the model's predictions (Pred.) of growth stage, dry matter (DM), and cumulative evapotranspiration to those measured (Meas.).

	Anthesis		Physiological Maturity		Above-ground Dry Matter		Grain Yield		Cumulative ET	
Treatment	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.
	(--------- Day of Year ---------)				(---------- g DM m^{-2} ----------)				(--- mm ---)	
1992-1993										
Dry	94	84	134	127	1334	1528	602	648	473	457
Wet	94	84	134	133	1813	1960	823	825	594	625
1993-1994										
Dry	93	93	133	133	1159	1348	525	605	439	436
Wet	93	96	133	141	1814	1893	831	804	637	658

Table 2. Model Predictions with Input of CWSI Measurements and Percent Difference (%Dif.) from the Measured Values (Table 1)

	Above-ground Dry Matter		Grain Yield		ET	
Treatment	Pred.	%Dif	Pred	%Dif.	Pred.	%Dif.
	(g DM m^{-2})		(g DM m^{-2})		(mm)	
1992-1993						
Dry - Predicted	1334	-13%	602	-7%	473	4%
D_iD$_a$	1341	-12%	584	-10%	473	4%
D_iD$_w$	1369	-10%	586	-10%	477	4%
W_iD$_a$	1450	-5%	619	-4%	521	14%
W_iD$_8$	1580	3%	651	0%	550	20%
1993-1994						
Dry - Predicted	1159	-14%	525	-13%	439	1%
D_iD$_a$	1203	-11%	508	-16%	446	2%
D_iD$_w$	1245	-8%	512	-15%	453	4%
W_iD$_8$	1509	12%	624	3%	577	20%

There was little difference in predictions of dry matter and ET when the measured canopy temperature in the Wet plots were used to specify dT_l versus specifying this value from VPD. However, there were certain days when the two were not in agreement, and this had a large impact on the PAW (data not shown). In one case, the CWSI used in the D_iD$_w$ simulation was 0.09 and 0.17 in the D_iD$_a$ simulation. The model predicted no stress on this day, and as the D_iD$_w$ simulation value was within 10% of the model, no change was made. However, for the D_iD$_a$ case, PAW was decreased and resulted in an under-prediction of PAW by 29 mm (the unmodified model under-predicted PAW by 9 mm on this day). Data from later dates resulted in a correction of this difference, so the impact on the results shown in Table 2 was minimal. However, this does point out an important sensitivity of this method to any over-prediction of water stress by the CWSI.

When the Wet irrigation treatments were simulated and CWSI for the Dry treatments input, the model predicted above ground DM and yields close to those observed for the Dry treatments. This close agreement must be balanced with the fact that the model underestimates these measurements and some of the improvement can be attributed to the time between CWSI readings when the PAW is higher due to the increased irrigation levels. The yields for W_iD8 simulations compared to the yields predicted by the model without modification are within 8 and 19 percent for the 1992-93 and 1993-94 seasons, respectively. The greater difference in the 1993-94 is related to the fact that CWSI measurements meeting the criteria specified in the methods section were not available later in the season, during grain fill.

The proposed method to integrate CWSI observations with CERES-Wheat does show promise; however, the method is very sensitive to any error in the CWSI that would indicate moisture stress when none is present. Further evaluations are planned to use this method to determine if CWSI observations will improve the model's predictions in individual treatment plots and to test different versions of the CWSI.

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