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IRRIGATION SCHEDULING USING A WATER BALANCE MODEL AND SOIL MOISTURE SENSORS

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INTRODUCTION

Irrigation water requirements of crops are highly variable across fields and throughout the growing season. This variability is caused by spatial differences in soil water holding capacity, crop evapotranspiration (ET_c) rates, weather (including rainfall distribution), non-uniformity of irrigations, and changing crop growth phases or crop conditions. Scheduling the amount and timing of irrigations based on field-specific soil water conditions is an effective technique that can increase irrigation application efficiencies while satisfying crop water requirements throughout the season.

Ideally, numerous soil moisture sensors can be installed across a variable field to determine soil water availability and irrigation requirements. However, this is currently cost-prohibitive. On the other hand, soil water balance models have been shown to be effective tools in estimating soil water deficits in the field (e.g., Andales et al., 2014). This paper demonstrates how a limited number of soil moisture measurements during the growing season (from strategically-placed soil moisture sensors or from soil moisture sampling) can improve the accuracy of irrigation requirements estimated by a soil water balance model.

IRRIGATION SCHEDULING

Water Balance Model

As the crop grows and extracts water from the soil to satisfy its ET_c requirement, the stored soil water is gradually depleted. In general, the net irrigation requirement is the amount of water required to refill the root zone soil water content back up to field capacity. This amount, which is the difference between field capacity and current soil water level, corresponds to the soil water deficit (D). The irrigation manager can keep track of D, which gives the net amount of irrigation water to apply. On a daily basis, D can be estimated using the following accounting equation for the soil root zone:

$$D_c = D_p + ET_c - P - Irr - U + SRO + DP \qquad [1]$$

where D_c is the soil water deficit (net irrigation requirement) in the root zone on the current day, D_p is the soil water deficit on the previous day, ET_c is the crop evapotranspiration rate for the current day, P is the gross precipitation for the current day, Irr is the net irrigation amount infiltrated into the soil for the current day, U is upflux of shallow ground water into the root zone, SRO is surface runoff, and DP is deep percolation or drainage.

The last three variables in equation 1 (U, SRO, DP) are difficult to estimate in the field. In many situations, the water table is significantly deeper than the root zone and U is zero. Also, SRO and DP can be accounted for in a simple way by setting D_c to zero whenever water additions (P and Irr) to the root zone are greater than $D_p + ET_c$. Using these assumptions, equation 1 can be simplified to:

$$D_c = D_p + ET_c - P - Irr \qquad \text{(if } D_c \text{ is negative, then set it to 0.0)} \qquad [2]$$

Take note that D_c is set equal to zero if its value becomes negative. This will occur if precipitation and/or irrigation exceed ($D_p + ET_c$) and means that water added to the root zone already exceeds field capacity within the plant root zone. Any excess water in the root zone is assumed to be lost through SRO or DP. Details of the operational implementation of equations 1 and 2 for tactical irrigation scheduling are described by Andales et al. (2014, 2015). The water balance approach is used by online irrigation scheduling tools such as the Water Irrigation Scheduler for Efficient Application (http://wise.colostate.edu/) and some other tools listed at https://irrigationinnovation.org/tools-weather-et-networks/schedulers-calculators-assessment-tools/.

Correcting the Model using Soil Moisture Sensors

Errors in estimating D_c using the water balance approach can accumulate through time. Errors in soil, weather, or irrigation inputs, and modeled values of ET_c can affect the accuracy of D_c estimates (Andales et al., 2014). It is a good practice to occasionally check if D_c from equation 2 is the same as the actual deficit in the field (e.g., from soil water content readings using soil moisture sensors). Remember that D_c is the difference between field capacity and current soil water content. Therefore, the actual deficit in the field can be determined by subtracting the current soil water content from the field capacity of the root zone.

If D_c from equation 2 is very different from the observed deficit, then use the observed deficit as the D_c value for the next day. These corrections are necessary to compensate for uncertainties in the water balance variables. Field measurements of current soil water content can be performed using the gravimetric method (weighing of soil samples before and after drying) or using soil moisture sensors. Peters et al. (2013) and Sample et al. (2016) summarize common types of soil moisture sensors that are used for irrigation management. For any type of sensor, calibration for local soils is recommended to obtain reliable soil water measurements (Varble and Chávez, 2011).

IMPACTS OF SOIL MOISTURE CORRECTIONS ON ACCURACY

To demonstrate the impacts of soil moisture corrections on the accuracy of an irrigation scheduler, irrigation and soil moisture records (2010 – 2012) from a furrow-irrigated corn field (13 acres) near Greeley, Colorado were used. Corn was planted in early to mid-May in rows spaced 30 inches apart. Furrow irrigations were applied by gated pipe equipped with a flow meter. The soil was predominantly Nunn clay loam and the corn crop was assumed to have a 42-inch root zone when it reached peak vegetative stage. During the 2010 to 2012 growing seasons, gravimetric soil water content measurements of the root zone were taken weekly from June to September. The soil samples were taken approximately mid-point of the field length to represent average soil water conditions along the furrow length. Samples were taken in the following depth increments: 0-6, 6-12, 12-18, 18-24, 24-36, and 36-42 inches from the ground surface. The gravimetric water contents were converted to volumetric water contents using measured soil bulk densities of the soil layers. The volumetric water contents were then used to calculate the actual soil water deficit in the root zone. In this example, the gravimetric measurements were used to represent corrections that can be made using any measurement device, including soil moisture sensors.

An automatic weather station (Station GLY04; www.CoAgMet.com) approximately 2000 ft (610 m) from the field provided daily rainfall, and weather data used to estimate ET_c. The daily soil water deficit in the corn root zone was calculated using a water balance model (equation 2) as described by Andales et al. (2014). Observed deficits that were measured in the field were then used to correct the water balance model. For reference, each weekly observed deficit was input into the model to simulate weekly corrections. Then, the model was ran using successively less frequent deficit corrections: bi-weekly, monthly, and using only the first observed deficit (initial only).

Figure 1 shows the soil water deficit curves during the three growing seasons. The daily deficits (net irrigation requirement to refill the root zone to field capacity) are shown as negative values, while precipitation (Precip) and irrigation amounts are shown as positive values. For each year, four deficit curves are shown according to decreasing frequencies of correction: weekly, bi-weekly, monthly, and initial only. Note that the modeled deficit curves tend to deviate more from the observed deficit values (orange squares) as the corrections become less frequent. In general, the largest deviations occurred when only one observed deficit value (initial only) was used in the water balance model. This demonstrated that more frequent soil water corrections can significantly improve the accuracy of soil water deficit estimates throughout the season.

Table 1 provides a summary of root mean square error (RMSE; average error of modeled D_c compared to observed D_c) and index of agreement (if d = 1.0, then there is perfect agreement between modeled and observed D_c) during the three growing seasons. These two statistics confirm what was shown in Figure 1 – more frequent corrections of D_c in the water balance model led to smaller errors (lower RMSE) and better agreement between modeled and observed D_c (higher d). One exception was the slightly lower index of agreement for bi-weekly corrections (d = 0.52) in 2011 compared to monthly corrections (d = 0.57). In this case, the dates of the monthly corrections coincided with times when the model was deviating more from observed D_c and the corrections caused larger reductions in errors at subsequent times. This can be seen in the 2011 graph in Figure 1, where monthly corrections on 9/6/2011 and 10/4/2011 overcame large errors in D_c.

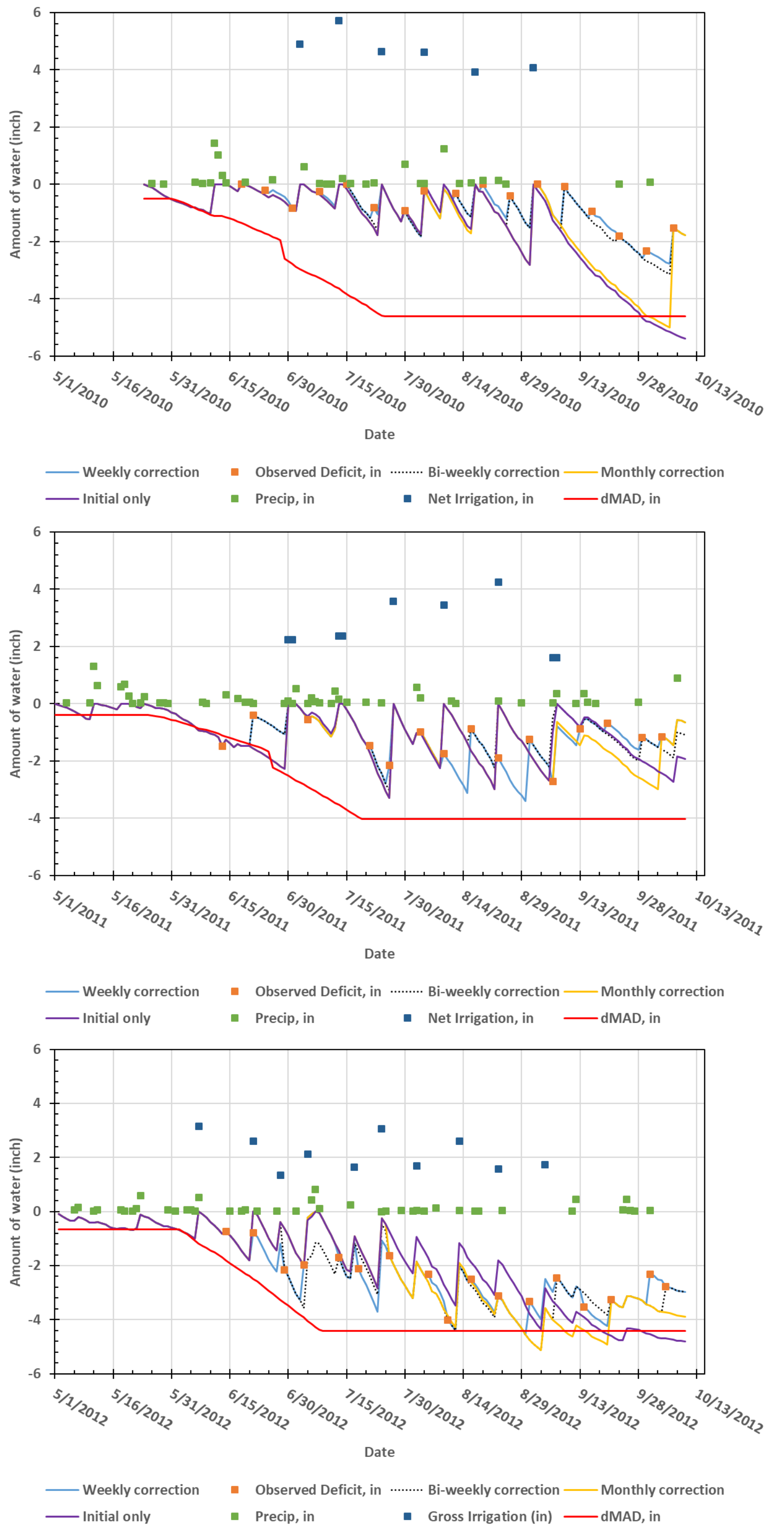

Figure 1. Modeled daily soil water deficits (D_c) for furrow-irrigated corn at Greeley, Colorado in 2010, 2011, and 2012. For each year, four D_c curves are shown with weekly, bi-weekly, monthly, and one-time (initial only) corrections based on observed deficits. The management allowed depletion (dMAD) represents the assumed threshold deficit at which corn begins to experience water stress.

Table 1. Impact of corrections on the accuracy of soil water deficit (D_c) calculations of an irrigation scheduler for corn in Greeley, Colorado (2010 – 2012). Weekly corrections were excluded, as they would have shown "perfect" agreement (RMSE = 0.0 in.; d = 1.0) because modeled D_c would be the same as observed D_c.

	Frequency of soil water deficit corrections		
Year and statistics[a]	Bi-weekly	Monthly	Initial only
2010 (n = 17)			
RMSE (inch)	0.21	1.00	1.41
d	0.98	0.76	0.68
2011 (n = 15)			
RMSE (inch)	0.92	0.95	1.02
d	0.52	0.57	0.43
2012 (n = 17)			
RMSE (inch)	0.66	0.83	1.09
d	0.89	0.86	0.76

[a]n = number of soil water deficit observations, RMSE = root mean square error (smaller values indicate smaller average errors), d = index of agreement (1.0 indicates perfect agreement between modeled and observed values; 0.0 indicates no agreement)

CONCLUSIONS

Water balance models and soil moisture sensors can be complementary components of an irrigation scheduling system. While models can provide acceptable estimates of net irrigation requirements, their errors can accumulate through the growing season. On the other hand, currently available soil moisture sensors can be expensive to install in all fields at multiple depths in the root zone; and they can be affected by hardware failure or calibration drift. Using occasional soil moisture measurements within the growing season to correct water balance models can be an effective approach to take advantage of both technologies. This paper demonstrated that more frequent corrections in the model can significantly reduce errors in estimated soil water deficits compared to using only one initial measurement at the start of the irrigation season.

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