When to irrigate? Testing the technologies available to estimate soil water in cotton systems

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Abstract

Australian cotton irrigators are continuously meeting challenges of water scarcity with technological innovation to improve their water resource management. A popular optimisation technique is to time irrigation applications based on a soil water content refill point. Point-source soil water measurements can give a current soil water status (*e.g*. using a neutron moisture meter (NMM)), but do not provide any predictive capacity to assist in planning future irrigations. We compared the accuracy of two methodologies to calculate soil water content with predictive capability: HydroLOGIC software (crop model) and IrriSAT software (Kc approach derived from NDVI satellite images), using calibrated NMM measurements as a standard. To enable a fair comparison of the two technologies in HydroLOGIC, the soil water was not corrected by inputting soil water measurements, with just the crop parameters and irrigation dates entered up until the run date. IrriSAT had slightly higher correlation (r = 0.82) with NMM readings compared with HydroLOGIC (r = 0.75) when averaged across the measurement period. However, the accuracy varied significantly during different periods which could significantly impact on irrigation timing. During early to peak flowering IrriSAT overestimated NMM deficits by 20-30 mm, which if relied on would result in irrigating much earlier than required whereas HydroLOGIC run without any soil water inputs underestimated crop water use after cut-out. The data suggested measured soil water through instruments such as NMMs can be used in a combined approach with predictive software to monitor soil moisture and enable irrigators to predict more accurately the timing of future irrigations.

Key Words

Irrigation scheduling, cotton, Ozcot, IrriSAT, plant available water

Introduction

Irrigation is a key component for crop and pasture production in Australian agricultural systems. Quantifying volumetric water content (VWC) is important to develop an estimation of plant available water (PAW), a value that has become a key component of irrigation management. Since the 1980s, point source devices such as capacitance probes and neutron moisture meters (NMMs) have been used to schedule cotton irrigation. These technologies are limiting, as they only measure one point within a field. Modern software developments allow irrigators to predict the fluctuation of soil water deficits, based upon climatic and agronomic data inputs, and remotely-sensed imagery. These programs use estimations of daily crop evapotranspiration (ET_C) as a means of estimating future PAW deficits (Liu *et al*. 2017). ET_C is a plant or crop's estimated total water use per day and is typically calculated with the use of reference crop evapotranspiration values (ET_O) and crop coefficient values (K_C). The generic crop coefficient approach utilises the following equation:

$$ET_C = ET_O * K_C,$$

where ET_C and ET_O are in mm d^{-1}, whilst the crop coefficient is dimensionless (Allen *et al*. 1998). IrriSAT is a cloud-based software for irrigated cotton systems, which utilises remote satellite imagery and climate data to estimate crop water use and soil moisture deficits regularly, using site-specific calculations for ET_O and K_C (Hornbuckle *et al*. 2015). The program allows users to obtain spatial normalised difference vegetation index (NDVI) data that demonstrates field variability throughout a growing season, as well as predict SWC with minimal need to physically enter the crop for soil or agronomic measurements. HydroLOGIC is a predictive software package that utilises the OZCOT crop model, which simulates cotton development based upon agronomic and climatic parameters (Hearn 1994). This model is incorporated into a crop scenario evaluation with field-specific parameters and local weather information to predict outputs including crop yield, daily ET_C and PAW. There is limited research available that compares the predictive capabilities of both IrriSAT and HydroLOGIC with actual direct or gravimetric soil moisture measurements. This project aims to compare different methods of estimating soil moisture status within an irrigated cotton system. Three different technologies/methodologies are studied and compared: NMM, HydroLOGIC Software and the IrriSAT cloud-based program. The estimation of soil water deficits from NMM is used as a standard to which the other methodologies are compared.

Methods

Study area and experimental design

Field experimentation was conducted during the 2017-2018 cotton season, at the Australian Cotton Research Institute, Narrabri N.S.W. (30^0 11' 47" S, $149^{'}$ 31" E). The field was approximately 4.25 ha and watered via flood irrigation with syphons. The soil was a Grey Vertosol, which has high fertility, high water holding capacity and with cracking-clay characteristics. The field was separated into 31 plots for an irrigation experiment run by CSIRO with plots allocated in a randomised complete block design. For the analysis of soil water content, only 13 of these plots were used. The plots had the same agronomic treatments and irrigation treatments/timing. Plots were approximately 30 m x 16 m in size. The field was planted with variety *Sicot 746B3F* (Bollgard III Roundup Ready Flex) cotton, sown at 1 m row spacing and a density of 14 seeds m^{-2}. Sowing occurred on November 1, 2017 with an average plant establishment of 10.8 plants m^{-2}. All plots received approximately 200 kg ha^{-1} nitrogen (applied as urea pellet – 46%N) prior to planting, and irrigated the day following planting to achieve a full moisture profile.

Gravimetric analysis for neutron moisture probe calibration

Aluminium access tubes were installed in the centre rows of each plot of Field A2 to a depth of 130 cm, installed halfway down the row and in the middle of the raised beds. Moisture readings were conducted in each plot on 15 separate dates, either 24 h before or 48 h after irrigation events in the field. Readings were taken with a Model CPN 503 Elite Hydroprobe ™ NMM. Measurements with this device were taken at depths of 20 cm, 30 cm, 40 cm, 50 cm, 60 cm, 80 cm, 100 cm and 120 cm. Twenty-five gravimetric cores (150 cm depth) were extracted from Field A2 on 6 separate dates in order to create independent calibrations for the NMM. Cores were extracted to 150 cm, divided at intervals that reflected the measurements depths of the NMM. NMM readings were taken at the site of coring near-simultaneously. Gravimetric core samples were weighed before and after oven drying, at 80^{o}C for 72 h. Volumetric water content (VWC) was determined through calculating gravimetric water content and then use of an existing bulk density characterisation for the field.

HydroLOGIC

Agronomic measurements required for the OZCOT model within HydroLOGIC were taken on 5 different dates. The necessary measurements, taken on a randomly selected metre within measurement row of each plot, were squares, green-bolls and open bolls per m^2. Light interception readings were also taken with an Accupar LP-80 Ceptometer device and converted into leaf area index (LAI). Measurements were taken on 73, 83, 93, 105 and 120 days after planting (DAP). Other necessary data gathered included all in-crop rainfall for the field, past weather data including maximum/minimum temperatures, rainfall and radiation (obtained from the nearby CSIRO Myall Vale weather station). Simulations of daily soil moisture deficits and crop evapotranspiration were run for each plot on the measurement dates, with only the agronomic and irrigation information supplied up until the run-date. Version 2.2.0 of HydroLOGIC was used.

IrriSAT cloud-based software

The current online version of IrriSAT was used to estimate soil moisture deficits for each plot. KML files describing geographic boundaries of each plot were created in Google Earth with known GPS field coordinates. The files were uploaded into *IrriSAT* to create individual survey plots. *CSV* files were downloaded for each field containing daily ET_C, ET_O, K_C and estimated soil moisture deficit values for each plot.

Statistical analysis

All data analysis was conducted in the software RStudio ® (Version 1.0.153). The accuracy of NMM to measure PAW deficits were compared with the gravimetric core measurements. Count rate ratios from the NMM measurements and volumetric soil moisture were calculated, and a linear regression was run between measurements of PAW deficits to a depth of 120 cm. Overall deficit estimates of each treatment were compared with NMM to derive overall correlations for the season. The *goof* (goodness of fit) function within the spectroscopy package in R was used for this analysis. Lin's concordance correlation coefficient (LCCC) and the root mean square error (RMSE) were used to assess the quality of models in the regression analysis when comparing NMM relationships with other methodologies. The statistical mean of these residuals was also used to analyse the bias of these relationships, to determine whether each methodology was over- or under-estimating the NMM values.

Results and Discussion

IrriSAT (r = 0.82) was slightly more accurate than Hydrologic (r = 0.75) in estimating PAW deficit throughout the whole season compared with NMM (Table 1), producing a high LCCC of 0.8 and 0.74, respectively, compared with NMM (Table 1). All of the methodologies displayed a close group of data at lower values of deficits observed. IrriSAT and HydroLOGIC estimations correlated strongly throughout the season, producing a high LCCC of 0.8 and 0.74, respectively, compared with NMM (Table 1). IrriSAT and HydroLOGIC's daily ETc estimations were also compared throughout the whole growing season. HydroLOGIC produced larger predictions of ETc during the early stages of crop development, whilst IrriSAT had significantly lower estimations in the first 50 DAP. IrriSAT then started to follow the expected rise in ETc with HydroLOGIC throughout the peak flowering to maturity stages. IrriSAT developed higher ETc values during the last 20 days of crop development, whilst HydroLOGIC predicted a fall. These ETc estimations are presented in Figure 1 for plot 13, which correlated best with NMM for both methods.

When the correlations were analysed throughout different stages of plant development, HydroLOGIC correlated more closely with most NMM readings for the first 70 days of development than IrriSAT. The software's underlying crop model, OZCOT, grows the crop on a daily time step; crop growth and development is adjusted with the agronomic and climatic data inputs. Some of its limitations may be due to a lack of agronomic information being inputted into the model. Richards *et al*. (2008) found that factors not accounted for in the software, such as severe pest damage, may produce inaccurate estimations too. Still, even without being corrected with soil water measurements, it outperformed the IrriSAT program up until peak flowering stages of the crop. The primary input relied upon by IrriSAT to develop its daily ET_C estimations is the NDVI imagery. Between crop emergence and peak flowering (approximately 80 DAP), the crop canopy does not produce a full coverage, and so each pixel will encounter a significant 'brown' area that may affect its interpretation of the crop coefficient. This may explain why it develops significantly lower ET_C estimations during earlier crop development. The satellite data in this experiment did not encounter many issues in terms of visibility, with only one pass-over period encountering zero visibility (due to cloud cover) at 68 DAP, whereby the program overrides the crop coefficient to become zero. The temporal resolution of its Sentinel satellite is 5-10 days, and 8-16 days for the two Landsat satellites (Hornbuckle *et al*. 2015). This could provide issues for irrigators during seasons with significant cloud cover, as repeated pass-overs with zero visibility would give inaccurate predictions of the ETc and develop an unconvincing estimation of PAW deficits. It would be useful to compare these different methodologies over more than one season to assess how different seasonal sources of variation may alter their performance. For example, seasons of excessive or very limited rainfall, significant pest/disease incidences, or periods of heavy cloud cover may affect the IrriSAT reliability. A combinational approach that could use continuous sensor data, from devices such as NMM or EM38, to correct the predictive capabilities of IrriSAT or HydroLOGIC throughout the season, may be considered too. HydroLOGIC and IrriSAT estimations in this study produced very strong correlations. An integrated approach coupled with the weather forecast may provide irrigators with more accurate predictions on which to base their irrigation decisions.

Table 1. Relationship between and regression values for IrriSAT, HydroLOGIC and NMM deficit readings for the whole season.

Relationship	Correlation factor (r)	r^2	LCCC	RMSE	Bias
IrriSAT - NMM	0.82	0.67	0.80	20.76	5.58
Hydrologic - NMM	0.75	0.55	0.74	24.09	4.52
IrriSAT - HydroLOGIC	0.83	0.69	0.83	18.78	-1.06

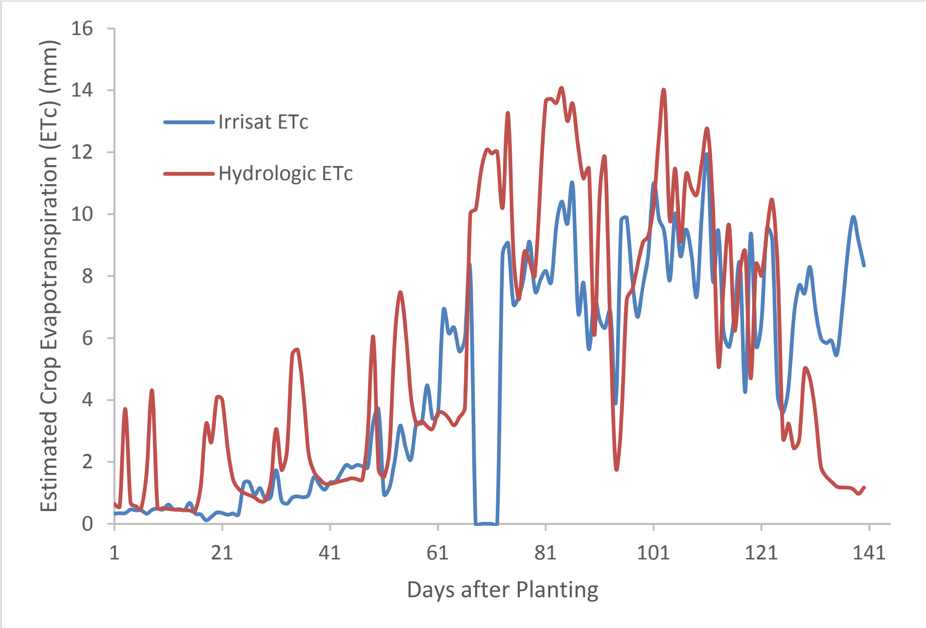

Figure 1. Daily Crop Evapotranspiration (ET_C) (mm) estimated by IrriSAT and HydroLOGIC throughout the season for Plot 13. Note that the sudden drop in IrriSAT ET_C around day 70 occurred due to cloud cover inhibiting the estimation of a crop coefficient (Kc)

Conclusions

This study compared three different methods of estimating soil moisture in an irrigated cotton system, particularly analysing their values of PAW deficits. Neutron moisture meter was firstly compared to gravimetric water measurements. Then, NMM was used as a 'standard' to compare against other methodologies such as HydroLOGIC and IrriSAT. The cloud-based IrriSAT program estimated deficits closest to that of NMM, closely followed by the Hydrologic software. This study was conducted over one irrigation season, with 15 daily measurements obtained from 13 plots in one field for NMM, IrriSAT and Hydrologic. IrriSAT and HydroLOGIC displayed temporal variation in their accuracy. IrriSAT, on average, overestimated NMM's deficit readings by approximately 20-30 mm during early flowering stages. HydroLOGIC underestimated NMM by similar amounts during later flowering/crop cut-out stages.

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