Dynamics of Evaporation and Transpiration in Overhead Sprinkler Irrigation

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Abstract
Evaporation and transpiration are the central components of the water balance in irrigated and rain-fed cropping systems. Their dynamics and the energy budget at pre, during- and post-overhead sprinkler are unique from other irrigation methods such as surface and drip. The photosynthesis process and net exchange of carbon dioxide (CO_2) are also different in wet canopy conditions compared with dry canopy conditions. However, these phenomena are not well understood in water and energy budget during the different phases of overhead irrigation events. A study was conducted in a cotton field using eddy covariance and sap flow systems to observe the dynamics of evaporation, transpiration, energy fluxes and exchange of (CO_2) in different phases of overhead irrigation. Data showed a marked increase in evapotranspiration rate during irrigation, a consequence of the high evaporation rate of water intercepted by the canopy. Canopy development has a distinct effect on evaporation rates. Evapotranspiration rates declined after irrigation as the canopy dried. Transpiration rates considerably reduced during irrigation but quickly recovered in the post-irrigation phase. The exchange of CO_2 decreased substantially during irrigation, possible due to a reduction in photosynthesis and closure of stomatal openings under wet canopy conditions. The energy fluxes show that sensible and latent heat act in opposite ways. Both may contribute to the evaporation of canopy intercepted water.

Key Words
Sprinkler irrigation, evaporation, transpiration, energy fluxes, net exchange of CO_2

Introduction
Irrigated agriculture is a significant contributor to the Australian economy. The irrigation industry is the primary water user in Australia consuming up to 75% of water used in agriculture (ABARES 2019). Farmers use a range of irrigation systems to apply water to crops. Common systems include surface (furrow, basin, or border check), sprinkler (micro sprinklers, travelling guns, booms, centre pivots, lateral moves, and solid set systems) and drip or trickle (ABS 2006). Historically, surface irrigation systems have dominated in Australian agriculture. However, farmers are increasingly adopting lateral move and centre pivot systems as water availability of declines. Many farmers in NSW have recently replaced their traditional surface system with a lateral move or center pivot supported through the Federal government scheme "Sustaining the basin-irrigated farm modernization" (STBIFM). However, there are some unresolved issues associated with sprinkler systems including canopy evaporation losses during irrigation (IAL 2019). Despite all the efforts, the dynamics of water balance and energy budget with the phenomenon of plant physiology in wet canopy conditions under sprinkler irrigation systems are still not well understood. Similar dynamics happen in rain events which is the primary water source in dryland cropping systems. A better understanding of the dynamics of water and energy budget in overhead sprinkler irrigation is essential to estimate the crop water use efficiency precisely. The objective of this paper is to illustrate the dynamics of change in evapotranspiration (ET), energy budget and photosynthesis pre-, during and post-irrigation that could influence the water balance.

Methods
The study was conducted in a sprinkler irrigated cotton field at the University of Southern Queensland, Toowoomba, Queensland, Australia. A portable sprinkler irrigation system was installed and positioned to ensure an irrigated cropped circle of 50 m diameter with the eddy covariance (ECV) system and other instrumentation located at the centre (Figure 1). Small and low angle (9◦) impact sprinklers (model 5024, Naan Dan Jain Irrigation Ltd.) at 9 m spacings were used. Sprinklers heights varied from 0.20 to 0.95 m according to the height of the crop.

The total evapotranspiration (ET) and the net exchange of carbon dioxide (CO_2) were measured by the ECV at pre-, during and post-irrigation periods. The ECV system comprised an infrared gas analyser (model

LI7500), coupled with a 3D sonic anemometer (model CSAT3) as shown in Figure 1. The high frequency (10 Hz) data was recorded with a data logger (CR3000). Raw data were processed to obtain sensible heat flux (H), latent heat flux (λE) and ET as given by Uddin et al., (2014a). Transpiration (T) was measured by using a sap flow system (Figure 1) consisting of six dynagauge sap flow sensors (model SGC10). Each sensor contained a digital interface and a hub to connect the sensors to the data logger. The sensors were installed on six randomly-selected plants of 10 to 13 mm stem diameter within the irrigated area and data were recorded on a smart data logger. Net radiation (Rn) was measured using a four-component net radiometer (model NR01). The soil heat flux (G) was measured with two heat flux plates (model HFP01) buried in two locations. One was installed between the rows and the other between plants. Two measurements were averaged to provide values of G. Temperature and relative humidity were measured using Temperature and relative humidity probes (model HMP 45c). Measurements were performed on relatively clear days typically through the middle of the day. The changes in actual evapotranspiration and transpiration were compared with reference evapotranspiration (ET_{ref}) measurements on different days and times using a non-dimensional technique. In this technique, a dimensionless variable (R_{et}) was calculated as the ratio of actual evapotranspiration obtained from the eddy covariance measurements (ET_{ec}) to reference evapotranspiration (ET_{ref}). Similarly, a dimensionless variable (R_f), was calculated as the ratio of transpiration (T) to ET_{ref}. The reference ET used in the process was calculated by the FAO approach as given by Allen et al. (1998).

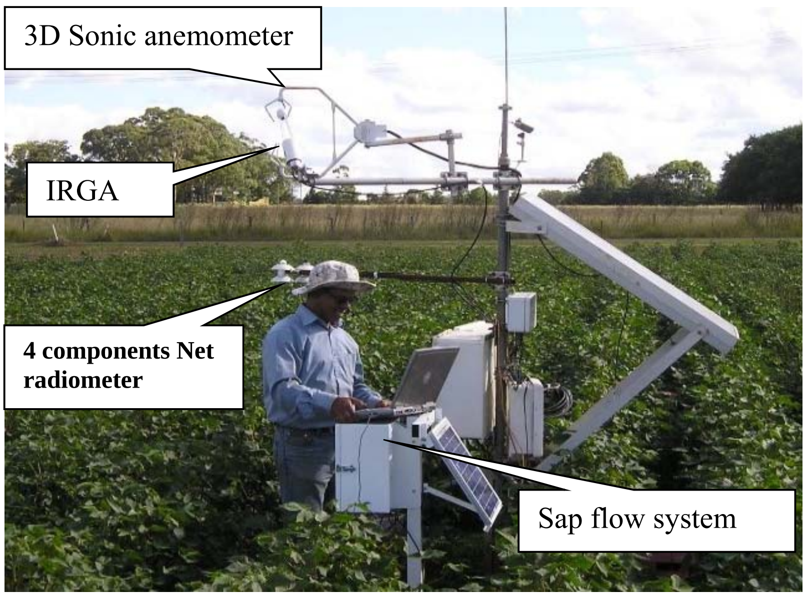

Figure 1. ECV and sap flow system installed at the centre of the cotton field.

Results

Evapotranspiration and net exchange of CO_2 trends

The effects of overhead sprinkler irrigation on the water balance are the increase in ET mainly as canopy evaporation and a substantial reduction in transpiration (Figure 2). Figure 2 clearly shows that the net exchange of carbon dioxide also decreases during the irrigation when the canopy remains wet. The principal features of changes in ET and transpiration during irrigation are;

- The rate of total ET substantially increased during and post-irrigation due to evaporation of water intercepted by the canopy.
- Transpiration decreased during and post-irrigation because of reduced stomatal opening due to wet canopy condition.
- Combined effect of reduction of photosynthesis activity and stomatal closure under wet canopy remarkably decreased the net exchange of CO_2.

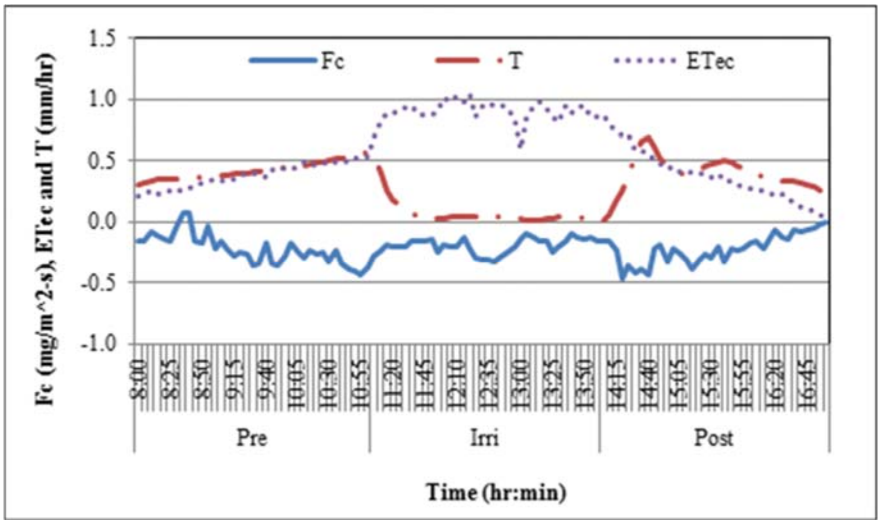

Figure 2. Evapotranspiration (ET_{ec}), Transpiration (*T*) and exchange of CO_2 (F_c) for a two hours irrigation event.

The mean ratios of ET_{ec}/ET_{ref} for the pre-, during and post-irrigation phases showed that the increase in *ET* was more significant during irrigation compared with post-irrigation for all stages of crop development (e.g. Table 1). The data show that *ET* increased between 37% and 82% depending on canopy coverage.

Table 1. Average values of ET/ET_{ref} at pre-, during- and post-irrigation periods at different stages of crop canopy coverage (%).

Crop stage	Average ET_{ec}/ET_{ref}			The increase of ET_{ec}/ET_{ref} during irrigation with respect to the pre-irrigation period	
	Pre	During	Post	R_{et}	%
Early (50% canopy)	1.01	1.38	1.19	0.37	37
Developing (75% canopy)	0.99	1.52	1.26	0.53	54
Full (100% canopy)	0.95	1.73	1.12	0.78	82

Similarly, a reduction in transpiration was determined by nondimensional values. The mean values of T/ET_{ref} in the post-irrigation phase were less than the pre-irrigation stage and higher than during irrigation (Table 2). The mean value of T/ET_{ref} for short duration (1/2 hr) irrigations was 0.48 (range 0.21–0.63), while for long duration (2-3 hr) irrigation the value was 0.82 (range 0.78–0.85, Table 2). The average reduction of transpiration was 82% (range from 81–% to 97%) in the longer irrigation events. Conversely, the average reduction was 45% (range from 20% to 60%) in shroter irrigation events.

Table 2. Average values of T/ET_{ref} at pre-, during- and post-irrigation of a sprinkler-irrigated field.

DOY	Date	Combination of irrigation (hr)			Average T/ET_{ref}			Reduction of T/ET_{ref} during irrigation	
		Pre	During	Post	Pre	During	Post	R_f	%
84	25 Mar	1	1/2	1	0.77	0.37	0.81	0.40	52
91	1 Apr	1	1/2	1	1.05	0.42	1.00	0.63	60
92	2 Apr	1	1/2	1	1.25	0.62	0.82	0.63	50
93	3 Apr	1	1/2	1	1.13	0.69	0.89	0.44	39
94	4 Apr	1	1/2	1	1.23	0.64	0.89	0.59	48
97	6 Apr	1	1/2	1	1.07	0.86	0.63	0.21	20
98	7 Apr	1	2	1	0.96	0.18	0.75	0.78	81
99	9 Apr	1	3	1	0.86	0.03	0.54	0.83	97
102	12 Apr	1	3	1	1.06	0.21	0.9	0.85	80
103	13 Apr	1	3	1	0.93	0.13	0.84	0.80	86

Effect of irrigation on energy fluxes

Two major energy fluxes (sensible (*H*) and latent) act in opposite ways. The *H*, originating from the surrounding drier (non-irrigated) area contributes to the available energy in the irrigated area. Due to this, the total ET was higher than the net radiation, and the *H* was negative during the irrigation (Figure 3). Conversely, the outgoing latent heat flux removes additional water vapour from the irrigated area due to the additional available energy contributed by the *H* flux. Tolk et al. (2006) reported that enhancement of ET due to advection (transport of heat and vapour by the mass motion of the atmospheric wind and gradient) could be an important factor in the water balance of irrigated crops in a semi-arid climate. The negative *H* indicates that the sensible heat flux supplies extra energy which is required to maintain the high evaporative rate (Figure 3). When latent heat flux is greater than net radiation; the sensible heat must be negative to supply the additional required energy (De Bruin et al. 2005).

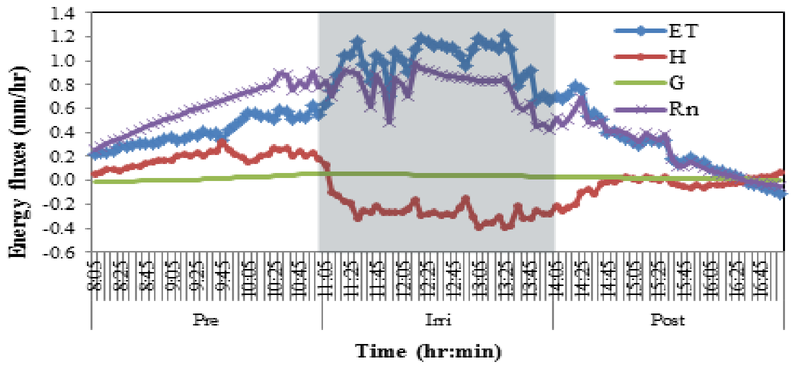

Figure 3. Components of energy fluxes in pre- during, and post-irrigation phases of a sprinkler-irrigated field.

Conclusions

This study showed ET rate increased markedly during and post-irrigation. This is likely due to the evaporation of water intercepted by the canopy. Decreasing rate of ET in the post-irrigation period indicates a drying of intercepted water remaining on the canopy. In both cases, the absolute ET rate was influenced by the growth stage of the crop. In contrast, transpiration measured by means of sap flow showed a considerable reduction in during irrigation before recovering quickly in the post-irrigation period. The energy budget indicated that evaporation could be considerably increased if advection happens in the irrigated area. Net exchange of CO_2 decreased substantially during irrigation. This may be the result of reduced photosynthesis and stomatal openings under wet canopy conditions. It is assumed that similar dynamics would occur in rainfall events, but would need to be investigated under rain-fed conditions. This could give a better understanding of water balance and a more precise estimation of water use efficiency.

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