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Agronomic and economic evaluation of irrigation strategies on cotton lint yield in Australia

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Abstract. Cotton is one of the most important irrigated crops in subtropical Australia. In recent years, cotton production has been severely affected by the worst drought in recorded history, with the 2007–08 growing season recording the lowest average cotton yield in 30 years. The use of a crop simulation model to simulate the long-term temporal distribution of cotton yields under different levels of irrigation and the marginal value for each unit of water applied is important in determining the economic feasibility of current irrigation practices. The objectives of this study were to: (*i*) evaluate the CROPGRO-Cotton simulation model for studying crop growth under deficit irrigation scenarios across ten locations in New South Wales (NSW) and Queensland (Qld); (*ii*) evaluate agronomic and economic responses to water inputs across the ten locations; and (*iii*) determine the economically optimal irrigation level. The CROPGRO-Cotton simulation model was evaluated using 2 years of experimental data collected at Kingsthorpe, Qld The model was further evaluated using data from nine locations between northern NSW and southern Qld. Long-term simulations were based on the prevalent furrow-irrigation practice of refilling the soil profile when the plant-available soil water content is <50%. The model closely estimated lint yield for all locations evaluated. Our results showed that the amounts of water needed to maximise profit and maximise yield are different, which has economic and environmental implications. Irrigation needed to maximise profits varied with both agronomic and economic factors, which can be quite variable with season and location. Therefore, better tools and information that consider the agronomic and economic implications of irrigation decisions need to be developed and made available to growers.

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Introduction

Cotton (*Gossypium hirsutum* L.) is one of the most important crops grown in Australia, covering ~200 000 ha in Queensland (Qld) and New South Wales (NSW). Cotton produces an average lint yield of 1800 kg ha^{-1} and contributes around AU$1.5 billion to the Australian economy each year (ABARES 2010). Irrigation plays a critical role in Australian cotton production, since around 85% of the cotton is irrigated (ABARES 2010), predominantly using furrow irrigation. In recent years in most zones of south-east Qld and northern NSW, cotton production has been severely affected by the worst drought in recorded history, with the 2007–08 growing season recording the lowest cotton yield over the last 30 years. During the last 2 years, due to more favourable growing seasons, farmers have partially recovered from the long and severe drought that began in 2002–03.

Australian farmers who adopt irrigated cotton are under increasing pressure to keep their farms economically sound because of reduction in water supplies due to reduced allocations of irrigation water and increased competition for water from other uses, such as industrial, urban, and environmental flows (Richards *et al.* 2008). In addition, the rising cost of energy and concerns over greenhouse gas emissions and climate change are putting additional pressure on growers (Grace *et al.* 2010). These constraints on water resources require irrigated cotton growers to reassess their current management practices to maximise their profit per unit of water applied.

Deficit irrigation (DI) has been suggested as one way to maximise profit per unit of water applied (English 1990). Zhang and Oweis (1999) defined DI as the practice of applying irrigation at drought-sensitive growth stages. Between these applications, irrigation is either limited or not applied, provided there is enough rainfall. The aim of DI is to stabilise crop yields and also to maximise crop water productivity rather than yields (Zhang and Oweis 1999). Successful DI management, however, requires a detailed understanding of the yield response to less irrigation water and its economic impact (Payero *et al.* 2009) and should be aimed at increasing the ratio of yield to water consumption (water-use efficiency) rather than maximising yield (Tennakoon and Milroy 2003). In addition, if DI is effectively managed, it may stabilise yield compared with non-irrigated crops and increase nitrogen (N)-use efficiency (Pandey *et al.* 2000).

For DI to be successful, it is important for farmers to understand not only the agronomic crop response to potential water stress caused by DI, but also its economic implication in terms of marginal value. The agronomic response to DI and its effects on profit maximisation are well documented (Constable and Hearn 1981; Tennakoon and Milroy 2003; Smith *et al.* 2005; Payero *et al.* 2009; Yeates *et al.* 2010). But yield maximisation is not necessarily coupled with profit maximisation. The costs associated with the input used to achieve maximum yield are not always taken into account. Watson *et al.* (2004) concluded that maximisation of the profit does better than yield maximisation for water and N management, regardless of the kind of agronomic management strategy. In fact, the impact of DI on the farmer's profit at a given DI is not well documented.

Crop models have been used to simulate both short- and long-term effects of water stress and its temporal interaction on daily crop growth and development rates throughout the growing season (Basso *et al.* 2001, 2007). The use of long-term recorded weather data allows us to take into account all of the weather extremes and to build probability functions of yield and marginal value for DI. Such models have been extensively validated and applied under a wide range of environmental conditions. The use of crop simulation models to simulate the long-term temporal distribution of cotton yields under DI and the marginal value for each unit of water applied is important in determining the economic feasibility of current DI practices.

The objectives of this study were to: (*i*) evaluate the CROPGRO-Cotton simulation model for studying crop growth under DI scenarios across ten locations in NSW and Qld; (*ii*) evaluate agronomic and economic responses to water inputs across the ten locations; and (*iii*) determine the economically optimal irrigation level.

Materials and methods

Crop growth model

Crop simulations were performed using the CROPGRO-Cotton model (Boote *et al.* 1998), which is part of the Cropping System Model (CSM) in DSSAT 4.5 (Decision Support System for Agrotechnology Transfer) (Hoogenboom *et al.* 2010). DSSAT 4.5 is a crop modelling and data analysis package widely used to simulate crop growth and development as a function of environmental conditions (weather and soil), crop genetics, and agronomic management strategies.

Model calibration and evaluation

The model was calibrated and evaluated using data from a cotton (*Gossypium hirsutum* L., Bollgard® II) field experiment conducted during 2007–08 and 2009–10 at the Kingsthorpe Research Station of Agri-Science Queensland, Department of Agriculture, Fisheries and Forestry. The station is located in southern Qld (27°30′44.5″S, 151°46′54.5″E; 431 m above mean sea level), in a subtropical climate. The soil at the site is a Haplic, self-mulching, black Vertosol according to the Australian Soil Classification (Isbell 1996). Soil properties for the research site used as input to the model are shown in Table 1.

The field experiment used a randomised complete block design with four irrigation treatments and three replications, with 200 kg N ha^{-1} of N fertiliser. The four irrigation treatments (T50%, T60%, T70%, and T85%) were irrigated when 50, 60, 70, or 85% of the plant-available soil water content (PASWC) was depleted. The T50% treatment received 228 mm of irrigation split into six applications, T60% received 83 mm in three applications, T70% received 82 mm in two

Table 1. Soil properties of the Kingsthorpe Research Station used for the calibration and evaluation of the CROPGRO-Cotton model

BD, Bulk density; OC, organic carbon; EC, soil electro-conductivity

Depth (cm)	Sand	Clay (%)	Silt	BD (g cm^{-3})	OC (%)	pH	EC (mS cm^{-1})	N (mg/kg)	P
0–10	7	76	17	0.89	1	7.3	0.239	28	110
10–20	7	76	17	1.03	0.8	7.2	0.416	86	77
20–30	7	76	17	1.02	0.6	7.5	0.345	61	25
30–40	7	76	17	1.03	0.5	7.9	0.348	49	19
40–50	6	76	18	1.03	0.4	8.1	0.355	39	32
50–60	6	76	18	1.05	0.3	8.2	0.349	36	40
60–70	9	72	19	1.05	0.2	8.3	0.334	34	45
70–80	9	72	19	1.01	0.1	8.5	0.32	28	49
80–90	9	72	19	1.02	0.1	8.5	0.314	24	46
90–100	9	72	19	1.06	0.1	8.5	0.363	25	41
100–110	10	73	17	1.07	0.1	8.6	0.308	21	43
110–120	10	73	17	1.08	0.1	8.6	0.336	18	35

applications, and T85% received no irrigation following the soil water depletions established for each treatment. Irrigation scheduling was based on weekly measurements of soil profile water content (at depth increments of 0.10 m) using the neutron probe method. Irrigation was applied using a solid-set sprinkler system. The growing season extended from mid-November (sowing) to mid-May (harvest).

Daily weather data used as an input to the model were recorded at the Oakey Weather Station by the Australian Bureau of Meteorology (www.longpaddock.qld.gov.au/silo/) for the period 1955–2010. Weather data included incoming solar radiation (MJ m^{-2} day^{-1}), maximum and minimum air temperature (°C), and rainfall (mm day^{-1}).

Model calibration is defined as the adjustment of the input parameters of the model in order to give an acceptable agreement between simulated and observed plant parameters (Boote *et al.* 1998). In this case the parameters subjected to model calibration were the cultivar genetic coefficients. The CSM-CROPGRO-Cotton has 18 cultivar coefficients that describe cotton growth and development. They were obtained by calibrating the model using measurements of developmental stages, cotton lint yield, and crop biomass for the T50% treatment obtained during the 2007–08 growing season. The model was then evaluated against biomass and grain yield measured in 2007–08 for the other three treatments (T60%, T70%, and T85%). In addition, the biomass measured in 2009–10 for all treatments was used to evaluate the model biomass prediction.

A further model evaluation was made for nine other major cotton-growing areas between northern NSW and southern Qld for the 2009–10 growing season (Table 2). Inside each area we chose zones that had the same cultivar as the one used in the calibration; the specific location, crop cultivar, management, and lint yield were taken from the Cotton Seed Distributor handbook (CSD 2010). The soil information was obtained through the APSoil application of APSIM (www.apsim.info/Wiki/APSoil.ashx), and the weather data from the Australian Bureau of Meteorology (www.longpaddock.qld.gov.au/silo/).

Long-term simulations

Long-term simulations were constructed based on the prevalent furrow irrigation practice of refilling the soil profile when the PASWC is <50%. When the threshold of 50% was reached, 11 different irrigation depths were applied for each location, which together with a non-irrigated scenario resulted in 12 irrigation scenarios. The seasonal irrigation applied varied with location due to differences in rainfall. For creating the 12 irrigation scenarios, the aim was to simulate growing conditions ranging from a non-irrigated to a fully irrigated crop by applying seasonal irrigation depths ranging from 0 to 600 mm.

Table 2. Locations and management used to evaluate the model and for long-term simulations

Location	State	Code	Sowing date	Plants m^{-2}	Growing season rainfall
Bourke	NSW	Bour	10 Oct.	9	182
Dalby	Qld	Dalb	10 Nov.	8	394
Dirranbandi	Qld	Dirr	07 Oct.	5	278
Goondiwindi	Qld	Goon	09 Oct.	11	367
Kingaroy	Qld	Kiga	01 Nov.	8	579
Moree	NSW	More	07 Oct.	11	367
Narrabri	NSW	Narr	09 Oct.	14	407
St. George	Qld	StGe	13 Oct.	8.3	287
Walgett	NSW	Walg	02 Oct.	9.5	284
Toowoomba	Qld	Twkg	02 Nov.	11	438

The model was evaluated using the root mean square error (RMSE) and the relative error (RE, %), calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} \quad (1)$$

$$RE = \left(\frac{|S_i - O_i|}{O_i}\right) \times 100 \quad (2)$$

where O_i is measured value, S_i is simulated value, and n is number of pairs of measured and simulated values.

Simulated grain yield (Y, kg ha^{-1}), evapotranspiration (ET, mm), and plant transpiration (Tp, mm) were used to calculate water-use efficiency (WUE, kg ha^{-1} mm^{-1}) and transpiration efficiency (Te, kg ha^{-1} mm^{-1}) using the following equations:

$$WUE = \frac{Y}{ET} \quad (3)$$

$$Te = \frac{Y}{Tp} \quad (4)$$

Economic analysis

The economic analysis included the calculation of total value of the product (TVP, AU\$ ha^{-1}), gross margin (GM, \$ ha^{-1}), and value of marginal product (VMP, \$ mm^{-1}) as:

$$\mathrm{TVP} = \mathrm{Y} \times \mathrm{P} \quad (5)$$

$$\mathrm{GM} = \mathrm{TVP} - [\mathrm{Cp} + (\mathrm{MFC} * \mathrm{Irr})] \quad (6)$$

$$\mathrm{VMP} = \Delta\mathrm{TVP}/\Delta\mathrm{Irr} \quad (7)$$

where P is cotton lint price (\$ kg^{-1}), Y is cotton lint yield (kg ha^{-1}), Cp is cost of production without irrigation (\$ ha^{-1}), MFC is cost of irrigation (\$ mm^{-1}), Irr is amount of irrigation (mm ha^{-1}), ΔTVP is change in total value of product (\$ ha^{-1}), ΔIrr is change in irrigation applied (mm^{-1} ha^{-1}). The VMP was calculated from the 12 irrigation scenarios described in the previous section, where the ΔTVP is computed between two different levels of irrigation.

The cost of production was calculated by adding the cost of each farm operation provided by the NSW Department of Primary Industries (DPI) website and was \$2700.07, excluding the cost of irrigation. The two variable costs related to fertiliser and ginning each contributed ~20% to total cost. An average lint price of \$2 kg^{-1} was assumed. The irrigation cost (MFC) of \$0.258 mm^{-1} (including the cost of water + application) was based on information from the NSW DPI and the Australian Cotton Production Manual (CRDC 2010). Since Power *et al.* (2011) showed that irrigation cost, including the cost of irrigation management, varied with irrigation method (from \$0.45 to 1.1 mm^{-1}), a sensitivity analysis of irrigation cost ranging from \$0.258 to 1 mm^{-1} at intervals of \$0.05 mm^{-1} was also performed to evaluate the impact of irrigation cost on the amount of irrigation needed to maximise profit. All other production costs were kept fixed in the calculations.

Debertin (2012) showed that the first-order condition for profit maximisation requires that VMP = MFC, which is the point where the VMP line intersects the MFC line, because when profit is maximised the slope of the profit function must be equal to zero. The details of such derivation are explained in Debertin (2012).

Results

Results of model calibration are shown in Table 3 and Fig. 1*a*. The RMSE of the simulation for cotton anthesis day (measured in days after sowing), maturity day, and lint yield were 2 days, 3.64 days, and 60.297 kg ha^{-1}, respectively. The genetic coefficients are presented in Table 4. Results of model evaluation for the 2007–08 and 2009–10 growing seasons are shown in Figs 1*b–d*, 2*a–d*, and 3. Crop biomass was well estimated for the other three irrigation treatments for the 2007–08 growing season. For the 2009–10 growing season, there were some discrepancies for the last two measured biomass dates for the T60% treatment, with measured values ranging between 8000 and 16 000 kg ha^{-1} for one date and between 7000 and 16 000 kg ha^{-1} for the other date (Fig. 2*b*). The cotton model evaluation for the ten sites for the 2009–10 growing season is shown in Fig. 3. Overall, the yield for all of the locations was well estimated, except for Goondiwindi and Moree where there was a model overestimation of 450 and 690 kg ha^{-1}, respectively. The RMSE between simulated and observed yield was 354 kg ha^{-1} and the RE was 13.7% (Fig. 3).

Table 3. Mean observed and simulated anthesis day, maturity day, and lint yield for CROPGRO-Cotton model calibration for the T50% treatment

Anthesis and maturity are days after sowing; ratio, simulated/observed

Variable	Mean observed	Mean simulated	Ratio	RMSE
Anthesis day	78	80	1.026	2
Maturity day	172	175	1.016	3.64
Lint yield (kg ha^{-1})	1232	1248	1.017	60.297

The average growing season rainfall at each irrigation amount for the ten sites is shown in Table 2. Growing season rainfall varied from 182 mm for Bourke to 579 mm for Kingaroy. The relationship between non-irrigated cotton lint yield and crop seasonal ET is showed in Fig. 4. Overall, there was a strong linear relationship between lint yield and ET ($y = 3.86x - 878$, $r^2 = 0.83$, $P < 0.001$). Bourke and Dirranbandi showed the lowest growing season ET and lowest lint yield, whereas Dalby, Toowoomba, and Kingaroy showed high seasonal ET and high lint yield (Fig. 4). Therefore, for subsequent analysis we chose three sites—one representative of the lower side of the ET–yield relationship (Bourke), one representative of the middle portion (St. George), and one from the high end of the relationship (Toowoomba) (Fig. 4).

Average simulated lint yields for the 55 years of simulation response to irrigation for the three selected locations are shown in Fig. 5. As expected, lint yield increased from the non-irrigated scenario to the scenario with the highest irrigation amount

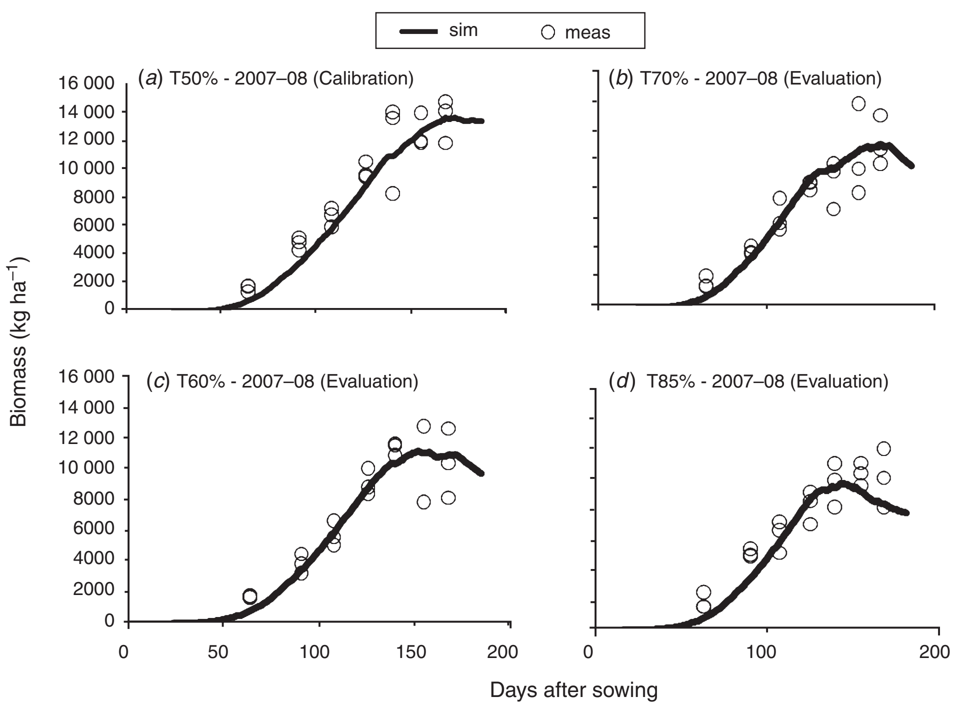

Fig. 1. Simulated (line) and measured (open dots) crop biomass for (*a*) the calibration plot (T50%), and (*b–d*) evaluations for the 2007–08 growing season. T50%, T60%, T70%, and T85% were irrigated when 50, 60, 70, or 85% of the plant-available soil water content was depleted.

Table 4. Description of the eighteen genetic coefficients used by the CSM-CROPGRO-Cotton model
Values were derived from model calibration for the cotton variety Sicala 60

No.	Genetic coefficient	Value	Units	Description
1	*CSDL*	23	hour	Critical short daylength below which reproductive development progresses with no daylength effect (for shortday plants)
2	*PPSEN*	0.01	h^{-1}	Slope of the relative response of development to photoperiod with time (positive for shortday plants)
3	*EM-FL*	48.46	Photothermal days	Time between plant emergence and flower appearance (R1)
4	*FL-SH*	10	Photothermal days	Time between first flower and first pod (R3)
5	*FL-s.d.*	12	Photothermal days	Time between first flower and first seed (R5)
6	*s.d.-PM*	34.28	Photothermal days	Time between first seed (R5) and physiological maturity (R7)
7	*FL-LF*	85.16	Photothermal days	Time between first flower (R1) and end of leaf expansion
8	*LFMAX*	1.4	mg CO_2 m^{-2} s^{-1}	Maximum leaf photosynthesis rate at 30°C, 350 ppm CO_2, and high light
9	*SLAVR*	175	cm^2 g^{-1}	Specific leaf area of cultivar under standard growth conditions
10	*SIZLF*	200	cm^2	Maximum size of full leaf (three leaflets)
11	*XFRT*	1.0		Maximum fraction of daily growth that is partitioned to seed + shell
12	*WTPSD*	0.19	g	Maximum weight per seed
13	*SFDUR*	5.5	Photothermal days	Seed filling duration for pod cohort at standard growth conditions
14	*SDPDV*	30.03	No. pod^{-1}	Average seed per pod under standard growing conditions
15	*PODUR*	14.7	Photothermal days	Time required for cultivar to reach final pod load under optimal conditions
16	*THRSH*	70	%	Threshing percentage: the maximum ratio of [seed/(seed + shell)] at maturity. Causes seeds to stop growing as their dry weight increases until the shells are filled in a cohort
17	*SDPRO*	0.153	g(protein) per g(seed)	Fraction protein in seeds
18	*SDLIP*	0.12	g(oil) per g(seed)	Fraction oil in seeds

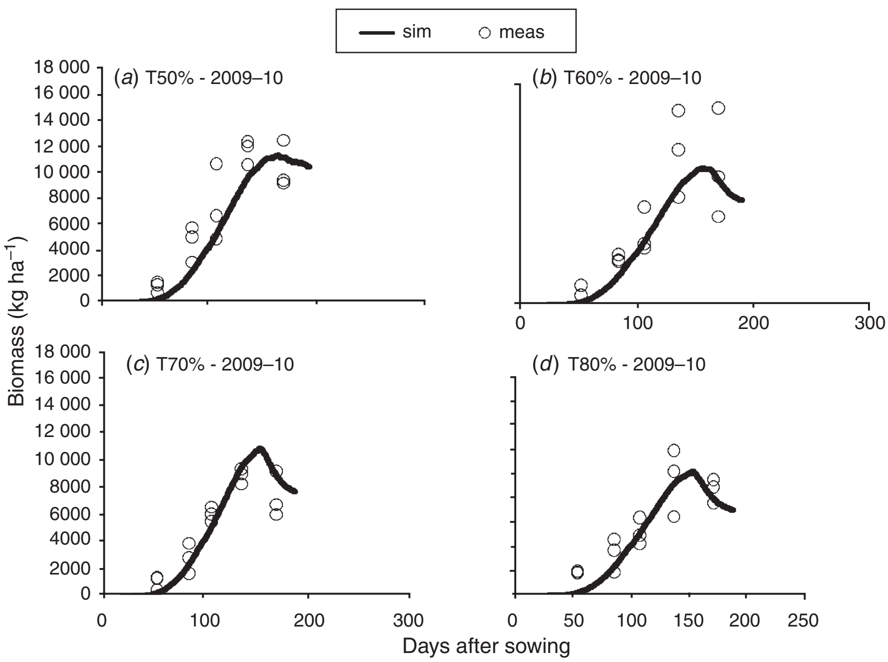

Fig. 2. Simulated (line) and measured (open dots) crop biomass evaluation for the 2009–10 growing season. T50%, T60%, T70%, and T85% were irrigated when 50, 60, 70, or 85% of the plant-available soil water content was depleted.

(scenario 12) and ranged between 260 kg ha^{-1} and a maximum of 2627 kg ha^{-1}. Lower yield variability among irrigation scenarios was simulated for Toowoomba. The average yield response to irrigation varied by location (Fig. 5), with the wetter location (Toowoomba) having a slower increase in yield with additional irrigation compared with the other, drier locations.

Figure 6 presents the relationship between the VMP and irrigation for the average yields simulated for the three locations; the horizontal line represents the irrigation cost (MFC) of \$0.258 mm^{-1}. Toowoomba showed the lowest water requirement to maximise profit (200 mm), whereas St. George and Bourke needed 530 mm of irrigation water to maximise the

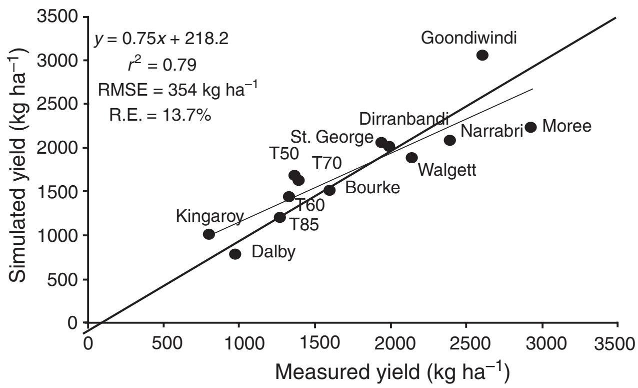

Fig. 3. Observed and simulated cotton lint yield for nine locations across northern New South Wales and southern Queensland for the 2009–10 growing season.

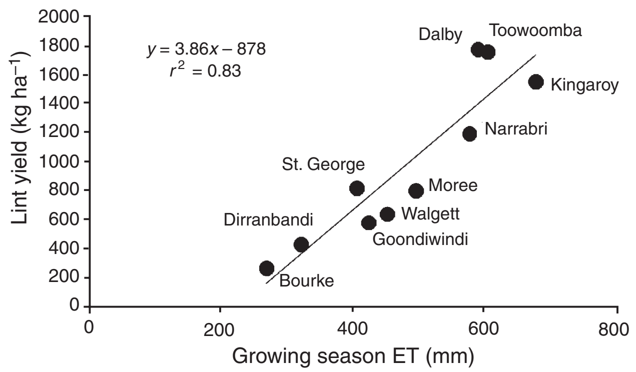

Fig. 4. Relationship between cotton lint yield and growing season average evapotranspiration (ET) for the non-irrigated scenarios at ten different locations.

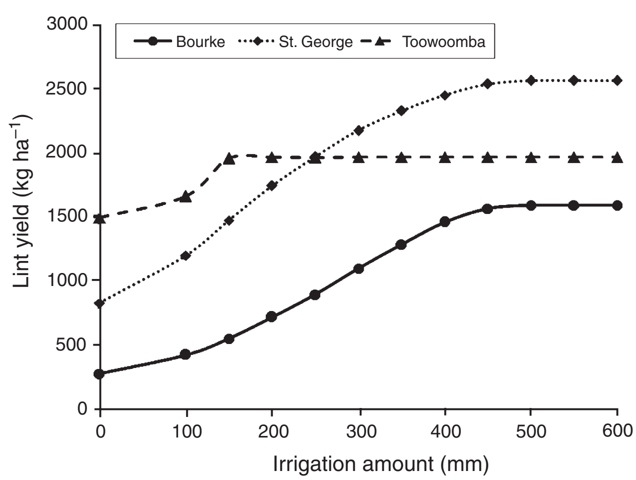

Fig. 5. Simulated yield response of cotton to 11 irrigation scenarios, plus non-irrigation for 3 locations. Each line represents the average of 55 years of simulations.

profit (Fig. 6). When the amount of water used to maximise yield was taken into account, Toowoomba needed 350 mm, St. George 550 mm, and Bourke 600 mm (data not shown).

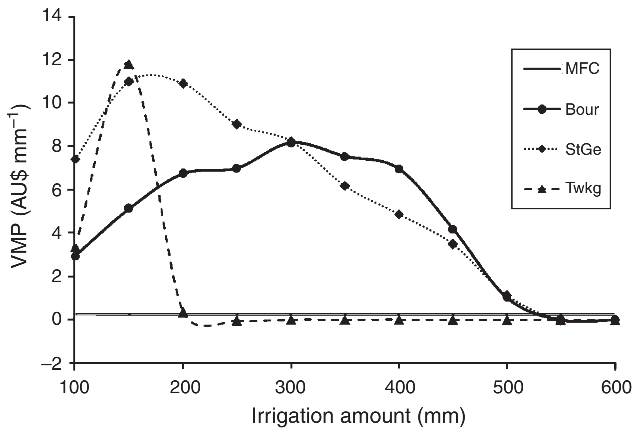

Fig. 6. Value of marginal product (VMP, AU\$ mm^{-1}) and the marginal factor costs (MFC, \$ mm^{-1}) at each simulated level of irrigation amount for the 3 locations. The MFC is set at \$0.258 mm^{-1}.

Table 5 shows the difference in Te, irrigation, rainfall, ET, Tp, WUE, lint yield, GM, and TVP between the irrigation amount at which the profit is maximised and the non-irrigation scenario for each location. The difference in Te was slightly negative for Dalby, with –0.1 kg ha^{-1} mm^{-1}; it was small for Kingaroy (0.8 kg ha^{-1} mm^{-1}) and Toowoomba (0.5 kg ha^{-1} mm^{-1}); and it was higher for Bourke, Goondiwindi, Moore, St. George, and Walgett, with 2.0, 2.9, 2.4, 2.6, and 2.2 kg ha^{-1} mm^{-1}, respectively (Table 5). Similar behaviour was shown for ET, Tp, and WUE. Lint yield showed greater differences in locations such as Goondiwindi, Moore, St. George, and Walgett, with 1907, 1820, 1739, and 1691 kg ha^{-1}, respectively (Table 5). Small differences in lint yield were simulated for the wettest locations of Dalby (336 kg ha^{-1}), Kingaroy (664 kg ha^{-1}), and Toowoomba (472 kg ha^{-1}). The irrigation amount at which profit was maximised ranged from 200 mm at Toowoomba to 530 mm at St. George and Bourke (Table 5). The differences in GM between the non-irrigated and the irrigation levels at which profit is maximised showed that in Dalby, there was a small difference in GM (\$581 ha^{-1}), whereas for the rest of the locations the differences were large, with Goondiwindi showing the largest profit difference at \$3685 ha^{-1} (Table 5).

Results of the sensitivity analysis are showed in Table 6. In Toowoomba, where the amount of irrigation needed to maximise profit was 200 mm at \$0.258 mm^{-1}, the increase in irrigation costs had little impact on the irrigation amount. In other places, for example Kingaroy, the amount of irrigation needed to maximise profit decreased from 420 mm at \$0.258 mm^{-1} to 240 mm at \$1 mm^{-1} (Table 6). At Bourke, where 530 mm of irrigation was required to maximise profit at \$0.258 mm^{-1}, this requirement only decreased by 30 mm at \$1 mm^{-1} (Table 6).

Discussions

The CROPGRO-Cotton simulation model successfully simulated cotton growth and lint yield under different irrigation scenarios and for different locations across NSW and Qld. Cotton yield response to irrigation varied across locations as a function of the growing season rainfall.

Table 5. Differences of transpiration efficiency (ΔTe), irrigation (ΔIrr), rainfall (Δrain), evapotranspiration (ΔET), transpiration (ΔTp), water use efficiency (ΔWUE), lint yield (Δyield), profit (ΔGM), and total value of the product (ΔTVP) between the non-irrigation and irrigation amount for which the profit is maximised at each location

For location codes, see Table 2

	Bour	Dalb	Dirr	Goon	Kiga	More	Narr	StGe	Walg	Twkg
ΔTe (kg ha^{-1} mm^{-1})	2.0	–0.1	1.9	2.9	0.8	2.4	1.3	2.6	2.2	0.5
ΔIrr (mm)	530	370	500	490	420	500	470	530	525	200
Δrain (mm)	5	1	7	7	-6	12	5	7	7	10
ΔET (mm)	282	72	216	217	70	202	161	208	237	66
ΔTp (mm)	248	68	188	226	83	214	172	186	240	66
ΔWUE (kg ha^{-1} mm^{-1})	1.9	0.2	1.8	2.5	0.7	2.1	1.3	2.1	2.0	0.5
Δyield (kg ha^{-1})	1289	336	1275	1907	664	1820	1293	1739	1691	472
ΔGM (AU\$ ha^{-1})	2501	581	2421	3685	1211	3510	2469	3348	3252	892
ΔTVP (AU\$ ha^{-1})	2630	672	2550	3814	1327	3639	2585	3477	3381	944

Table 6. Sensitivity analysis of irrigation (mm) needed to maximise profit at different irrigation cost (AU\$ mm^{-1}) for each location

For location codes, see Table 2

Site	Irrigation cost per unit irrigation															
	0.25	0.30	0.35	0.40	0.45	0.5	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.0
Bour	530	530	520	520	520	515	510	510	510	510	505	504	504	503	502	500
Dalb	370	365	340	283	277	270	265	260	255	250	248	242	240	237	235	230
Dirr	500	495	493	492	490	487	485	484	481	480	479	477	475	473	472	471
Goon	490	489	488	487	486	485	484	483	482	481	480	479	479	477	475	473
Kiga	420	300	292	290	285	280	277	273	270	268	265	263	260	255	252	250
More	500	499	497	495	493	491	490	489	487	485	484	482	480	479	477	475
Narr	470	469	465	460	457	450	445	440	430	425	420	415	410	405	402	399
StGe	530	529	527	525	523	521	520	519	517	514	512	510	510	509	507	505
Walg	525	523	520	517	515	512	510	507	505	503	500	499	497	495	493	490
Twkg	200	200	200	199	199	199	198	198	197	197	197	196	196	196	195	195

The CROPGRO-Cotton simulation model was well calibrated following the approach of minimum dataset as described by Boote (1999). Once the model is well calibrated and can well simulate the patterns of biomass accumulation, main developmental stages, and lint yield, and its evaluation confirms such behaviour, it can be applied in other places where cotton is grown, provided soil information and management information are available. In this case, the information was available and the model was able to simulate well the cotton lint yield in other locations of southern Qld and north NSW.

Cotton lint yield response to irrigation (Fig. 5) was closely related to the amount of rainfall at each location. At the wetter sites such as Toowoomba, Dalby, and Kingaroy, dryland lint yield was higher than at drier locations (Table 2, Fig. 3) and had slower rate of yield increase as irrigation increased. In areas such as Bourke, where cotton is often grown under rainfed conditions, the amount of rainfall during the growing season allows storage of enough soil water for production of acceptable lint yield. Rainfall before sowing allows uniform seed germination and can be used by plants later in the season when water demands are higher. Rainfall occurring from sowing to first flower adds to what is stored in the soil from the fallow period and can be used by crops around flowering when crop water demand is highest. In Australia, most of the soils where cotton is grown are heavy cracking clays with a high capacity of storing up to 150 mm of plant-available water (Tennakoon and Milroy 2003), and therefore if there is enough moisture in the soil profile at sowing, the amount of water to be applied as irrigation will be reduced (Bange *et al.* 2004). Interestingly, at Toowoomba the 228 mm of irrigation applied to the T50% treatment during the 2007–08 field experiment was similar to the 200 mm estimated by the model to maximise profit for that location.

Our results showed that the irrigation level needed to maximise cotton profit varied by location. For locations such as Toowoomba, where the amount of irrigation required for profit maximisation is relatively low, an increase in irrigation costs will not cause significant changes to this amount. This is also visible in the pattern of the VMP for the Toowoomba site (Fig. 6). At the point where VMP crosses MFC there is a steep slope, and therefore, any increase in MFC results in little change in irrigation amount. Bourke showed the opposite behaviour, where increases in MFC will cause significant changes in the irrigation amount needed to maximise profit. The reasons for such behaviour are in the differences in rainfall, ET, and growing conditions between sites. For example, in Bourke there is on average ~184 mm of rainfall during the growing season, which is lower than Toowoomba with 438 mm (Table 2). Bourke and Toowoomba showed growing season ET of 270 and 606 mm, respectively (Fig. 4). Therefore, to meet such demand, plants at Bourke will require more water than those at Toowoomba. The amount of water needed to maximise yield is always higher than needed to maximise profit. This means that in order to maximise yield, often the water is used beyond the point of profit maximisation, leading to negative environmental externalities and a lower economic return. For example, to maximise lint yield at Bourke, 600 mm of water is needed, whereas to maximise profit (at a cost of irrigation water of \$0.25 mm^{-1}), only 530 mm is needed (Table 6). With any increase in water prices, farmers respond by using less water in order to minimise economic losses and maximise yield; however, if their baseline is 600 mm rather than 530 mm they may not be able to keep their business viable.

The simulated irrigation amounts at which profit is maximised were always below the crop ET, meaning that the difference was supplied by rainfall and by water stored in the soil profile at sowing. Ritchie and Basso (2008) argued that under adequate water supply, transpiration efficiency can vary as a function of genotype, fertiliser management, and planting density. Results of this study showed that Te varied greatly at different irrigation amounts for some locations, whereas for others, Te did not change with irrigation level. Such differences in Te are driven by the difference in growing season rainfall for each irrigation scenario. For example, in locations such as Bourke, the differences in rainfall, ET, Tp, and irrigation amount among irrigation scenarios was large, causing large variations in Te. For sites such as Dalby, on the other hand, where changes in rainfall are less marked, ET and Te will not vary much between irrigation scenarios. For areas such as Dalby, Toowoomba, and Kingaroy, our long-term simulation study showed that production under less favourable rainfall conditions is feasible (Table 5).

Tennakoon and Milroy (2003) found that the average seasonal ET for cotton was 735 mm in the major cotton-growing areas, with an overall WUE of 2.7 kg mm^{-1} ha^{-1}. They calculated ET using a modified version of the model of Ritchie (1972). Results of this study agree with that finding. The average seasonal ET for the ten sites was 700 mm with a WUE of 3.4 kg mm^{-1} ha^{-1}. For this study, the Suleiman–Ritchie method to estimate crop ET was used (Hoogenboom *et al.* 2010). Our results also agree with the findings of Tennakoon and Milroy (2003) that, for ET values between 650 and 730 mm, lint yield for the ten locations reaches a plateau. Studies have shown that WUE is affected by irrigation timing (Tennakoon and Milroy 2003; Payero *et al.* 2009). For this study, however, irrigation was applied at the same time for all irrigation scenarios, and changes in WUE were therefore driven by total water input (irrigation + rainfall + soil water) rather than irrigation timing.

Conclusions

This study provided agronomic and economic quantification of cotton yield production under different irrigation scenarios and for different growing regions of Australia. In a cotton production area like Dalby, the Te and WUE were practically constant for different simulated irrigation amounts due to adequate growing season rainfall. In this case the application of 370 mm of water will maximise profit. In other areas, more irrigation was needed because the amount of growing season rainfall was too low. In these cases, the WUE changed with irrigation amount. Long-term simulation of different irrigation scenarios allowed estimation of the irrigation amount needed to maximise cotton profit at each of ten locations. Our results showed that the amounts of water needed to maximise profit and maximise yield are different, which has economic and environmental implications. However, the amount of irrigation needed to maximise profits varied with both agronomic and economic factors, which can be quite variable with season and location. Therefore, better tools and information that consider the agronomic and economic implications of irrigation decisions need to be developed and made available to growers.

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