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Irrigation for Crops in a Sub-Humid Environment

VII. Evaluation of Irrigation Strategies for Cotton

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Summary. Empirical functions to predict the nitrogen uptake, increase in LAI and minimum leaf water potential (LWP) of cotton were incorporated into a water balance model for the Namoi Valley, N.S.W. A function was then developed to describe the lint yield of irrigated cotton as a function of water stress days at 4 stages of development, total nitrogen uptake and days of waterlogging. A water stress day was defined as predicted minimum leaf water potential less than –1.8 MPa up to 90 days after sowing and –2.4 MPa thereafter; stress reduced yield by up to 40 kg lint ha^{-1} d^{-1} with greatest sensitivity at 81–140 days after sowing and when N uptake was highest. Nitrogen uptake was reduced by 0.98 kg per ha and yield reduced by 33.2 kg lint ha^{-1} for each day of waterlogging. The model was used to evaluate various irrigation strategies by simulating production of cotton from historical rainfall data. With a water supply from off farm storage, net returns (\$ Ml^{-1}) were maximized by allocating 7 Ml ha^{-1} of crop. The optimum practice was not to irrigate until 60 days from sowing and until the deficit in the root zone reached 50%. When the supply of water was less than 7 Ml ha^{-1} there was no advantage in either delaying the start of irrigation or irrigating at a greater deficit; it was economically more rational to reduce the area shown or, if already sown, to irrigate part with 6 Ml ha^{-1} and leave the rest as a raingrown crop. Irrigation decisions are compromises between reducing the risk of water stress and increasing the risk of waterlogging. The simulation showed that there is no single set of practices that is always best in every season; in a number of seasons practices other than those which on average are best, give better results.

Introduction

In the most recent paper in this series Constable and Hearn (1981) reported a four year study in the Namoi Valley, N.S.W. (149°47′E, 30°13′S) of the effect of irrigation and nitrogen on the growth and yield of cotton. The regime representing commercial practice yielded well every year but was always out yielded by at least one other treatment, the particular treatment depending on the rainfall pattern for the year. In an earlier paper Hearn and Constable (1981) analyzed a similar set of results for soybeans by defining a stress day, summing the number of such days experienced by each treatment, and then expressing yield as a function of stress days. The function was then used to evaluate by simulation the options available to a farmer for using a limited supply of irrigation water. This paper reports a similar analysis for cotton.

Procedure

The procedure, basically that used for soybean (Hearn and Constable 1981), was modified by the inclusion of nitrogen and involved four steps:

1. Collection of Data in the Field

Constable and Hearn (1981) described the experiments. The effect on cotton of irrigating at various soil water deficits, in combination with a range of nitrogen fertilizer rates, was studied for four seasons. There were 124 season × irrigation × nitrogen combinations. Yield was measured on all treatment combinations and LAI, nitrogen uptake (NUP) and leaf water potential (LWP) were measured on selected combinations. Cull et al. (1981) calibrated the Ritchie (1972) soil water balance model (WBM) for cotton in the Namoi Valley. Physiological data similar to that used for soybeans (Turner et al. 1978), including the response of stomata and photosynthesis to water stress, were collected concurrently near the experimental site by N. C. Turner, J. E. Begg and ourselves (unpublished).

2. Derivation of Leaf Water Potential and Nitrogen Uptake Functions

The WBM, updated with local parameters, was run retrospectively for the experimental treatments on which LWP and NUP were measured in order to give a revised estimate of the daily soil water balance and NUP were then expressed as a function of soil water status.

3. Derivation of Leaf Area and Yield Functions

The LWP and N uptake functions were then included in the WBM which was again run retrospectively to estimate N uptake and LWP of the experimental treatments on which they were not measured. The WBM was run again in order to develop functions to express increase in leaf area index (LAI) and yield in terms of nitrogen uptake, stress days (as indicated by LWP) and waterlogged days.

4. Simulation

The yield and LAI functions were put in the WBM to simulate production of a range of irrigation options using rainfall records for the previous 22 years at the Research Station and 95 years at Wee Waa, 11 km distant. Those simulations were then used to evaluate options available to farmers. Radiation and temperature for these simulations were estimated from the day of the year and days since the last rainfall, as described by Hearn and Constable (1981).

The functions derived in steps 2 and 3 were obtained by regression analysis. The independent variables were suggested by the main effects and interactions found by analysis of variance of the experimental results (Constable and Hearn 1981). Variables were excluded in order of significance, starting with the least significant, until the R^2 started to decrease. Extrapolation outside the range of the data can lead to serious errors when using such regression equations. The range of all variables in the equations used is given in Appendix I.

Derivation of Functions

Soil Water Status

In order to estimate the daily soil water deficit (SWD) for each treatment in the experiment the WBM was updated with locally derived parameters. With cotton, unlike soybeans, there was no evidence that the depth of rooting was affected by water stress experienced early in the season; consequently in the WBM, increase in the depth of the root zone was simulated using data of Cull et al. (1981) by setting the initial available water holding capacity at 110 mm and increasing it by 1 mm day^{-1} from 45 to 115 days from sowing.

The limit for the Stage I plant evaporation (energy limited) was left at 70% as in the original WBM in contrast to soybeans for which it was reduced to 60%. The function for the rate of plant evaporation (E_0) in Stage I is that of Cull (Personal communication):

$$E_p = E_0\,(0.156 + 0.283\ \mathrm{LAI})$$

where E_0 was estimated from solar radiation and the Priestly and Taylor (1972) equation with Ritchie's original value of 1.4 for the constant. The parameters for soil evaporation were the same as used for soybeans: 14 mm for the limit to Stage I (energy limited) and 7.83 mm for the Stage II constant.

Plant Water Status

Values of LWP measured at 1400 h were regressed on the estimated soil water deficit, evaporative demand and crop age to give the following relationship:

$$\mathrm{LWP} = 0.862 - 0.00909\ \mathrm{AGE} - 0.2293\ E_0 - 0.0273\ \mathrm{SWD} - 0.000157\ \mathrm{SWD}^2 + 0.00386\ \mathrm{SWD} \times E_0 \qquad (1)$$

$n = 61 \qquad R^2 = 0.85$

where LWP is in MPa, AGE is days from sowing, E_0 is evaporative demand and SWD is deficit as a percentage of the capacity of the current root zone. Figure 1 (a) compares the relationship between LWP and SWD described by (1) for cotton with that previously reported for soybeans for similar age and evaporative demand. In cotton LWP started to decline early and gradually as SWD increased while in soybeans the decline was delayed but steeper. The effect of E_0 was to reduce LWP of cotton more when WSD was low (Fig. 1 b); LWP can be reduced by either

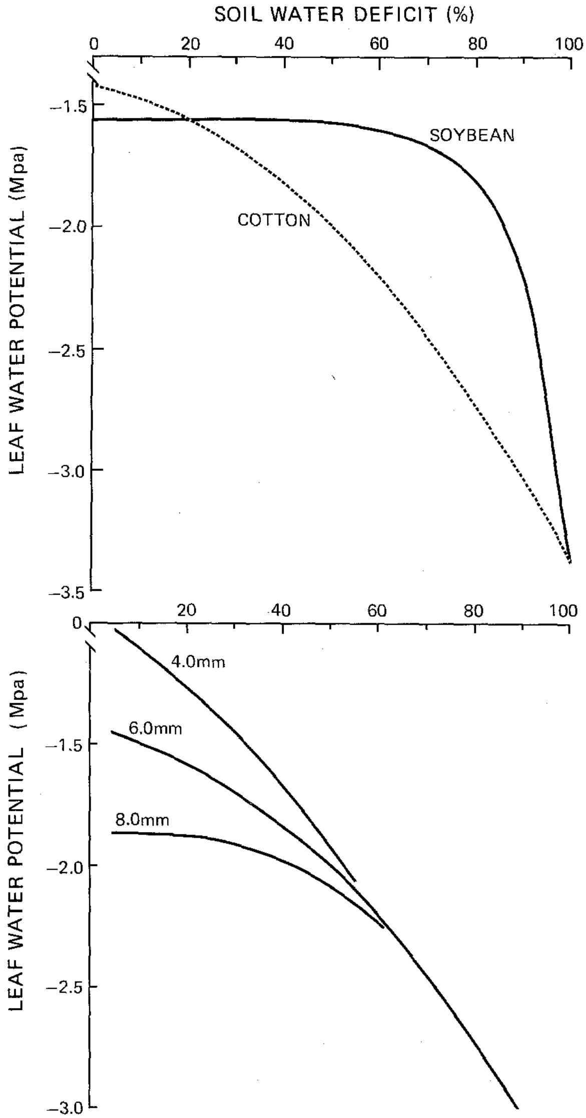

Fig. 1a and b. Leaf water potential and soil water deficit: **a** cotton compared with soybeans at 100 days from sowing with $E_0 = 6$ mm, **b** effect of E_0 on LWP of cotton at 100 days from sowing. Soybean relationship is from Hearn and Constable (1981)

increased demand (E_0) or limited supply (SWD), but the effects are not fully additive. For a given SWD and E_0 the effect of crop age is for younger crops to have a greater LWP because, it is postulated, roots are growing into deeper layers of moist soil.

Crop Water Stress

Not only did the relationship between LWP and soil water deficit in cotton differ from that previously found for soybeans, but the physiological data we collected with Turner and Begg (Personal communication) showed that the relationships between photosynthesis (PG) and LWP were also different. Figure 2 (a) shows that

PG in cotton was much less sensitive to decreasing LWP than in soybeans. The relationships between LWP and SWD (Fig. 1 a) and between PG and LWP (Fig. 2 a) are combined in Fig. 2 (b) to give the relationship between PG and SWD. Whereas in soybeans no decrease in PG was predicted until the deficit exceeded 60%, in cotton PG decreased gradually over the whole range and there was no threshold deficit below which PG was unaffected. Consequently it is not possible to define crop water stress in cotton on the basis of a threshold deficit, or LWP, below which PG decreased abruptly.

Grimes and Yamada (1982) studied the relationships between both vegetative growth (mainstem elongation) and fibre growth (length and weight) and LWP of cotton. Vegetative growth was greatest at the highest values of LWP ($\simeq -1.3$ MPa) and decreased linearly to zero when LWP reached -2.4 MPa; in our experiments, when vegetative growth was at its peak at 100 days, this LWP corresponds to a SWD of 70%. By contrast Grimes and Yamada found that fibre growth was unaffected by water stress until LWP fell to between -2.7 and -2.8 MPa, which in our

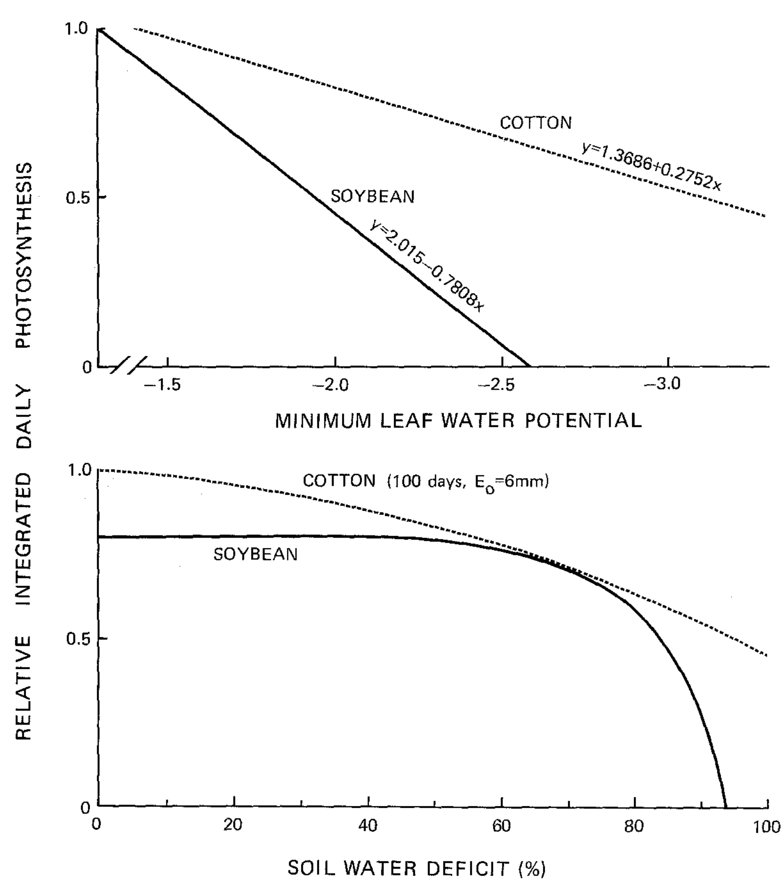

Fig. 2a and b. Integrated daily photosynthesis and water stress: **a** relationship with LWP, cotton from Turner and Begg (pers. comm.), soybean from Rawson et al. (1978), **b** relationship with soil water deficit derived from Figs. 1 and 2. Photosynthesis is expressed relative to that measured at minimal water stress experiments also corresponds to SWD of 70% at 130 days, when fibre growth was greatest. In our experiments vegetative and fibre growth are therefore likely to have ceased at a soil water deficit of 70%.

Waterlogging

Cotton is sensitive to waterlogging as well as water stress. Temporary waterlogging is the inevitable adjunct of furrow irrigation on this soil type. Oxygen diffusion rate was measured in the 1977/78 experiment (Constable and Hearn 1981), and Hodgson (1982) measured air filled porosity on adjacent sites. These measurements indicate that after inundation for the 8 to 12 h required to irrigate our experiments the soil was inadequately aerated for 2 to 4 days. During this period the estimated soil water deficit both in our experiments and Hodgson's was never greater than 25 mm. This figure was therefore taken as a threshold for waterlogging.

Nitrogen Uptake

Nitrogen uptake at maturity was measured on selected treatments (Constable and Hearn 1981). It was noted that:

(i) the uptake by unfertilized plots varied among the years, suggesting differences in available soil nitrogen,

(ii) uptake was less on frequently irrigated treatments, which would have experienced more days of waterlogging,

(iii) recovery of fertilizer nitrogen was less in rain grown crops, which experienced more stress.

The following relationship was fitted to the data from the 1976/77 experiment which was the only year with a wide range of both stress and waterlogging:

$$\mathrm{NUP} = 77.7 + 0.636\ \mathrm{FERTN} - 0.0316\ \mathrm{FERTN} \times \mathrm{STRDAY} - 0.983\ \mathrm{WL} \qquad (2)$$

$n = 16 \quad R^2 = 0.77$

where NUP is nitrogen uptake for the season, FERTN is nitrogen applied as fertilizer, both in kg/ha, STRDAY is number of days when the calculated soil water deficit is greater than 70% and WL is number of days when the calculated soil deficit is less than 25 mm, the values 70% and 25 mm being based on criteria described previously. The value for available soil nitrogen (SOILN) for 1976/77 was determined empirically from the intercept of equation (2) as 77.7 kg N per hectare. By substitution of the mean values for NUP, FERTN, STRDAY and WL for each year in equation (2), the following values of SOILN were obtained:

1974/75	93.0
1975/76	86.0
1976/77	77.7
1977/78	51.1

Using these values as the intercept in equation (2) with the actual values for FERTN, STRDAY and WL, NUP was estimated for each treatment and compared with measured values. The correlation coefficient was 0.73 ($n = 48$).

Leaf Area

The water balance model was run again for all treatments in which LAI was measured. The relative rate of increase in LAI was calculated for all sampling intervals up to 120 days. The following relationship was fitted to the data:

$$\begin{aligned} \text{RLAI} = & -6.05 - 2.219\ \text{LAI} + 0.013\ \text{SOILN} - 0.343\ \text{WL} \\ & + 0.388\ \text{LAI} \times \text{NONSTR} + 0.00878\ \text{LAI} \times \text{NUP} \end{aligned} \quad (3)$$

$n = 261 \quad R^2 = 0.44$

where LAI, WL, SOILN and NUP are as defined previously, NONSTR is number of days when the calculated deficit was less than 55%, selected empirically, and RLAI is relative rate of LAI increase $m^2\ m^{-2}$ day degree^{-1}, day degrees being over a base temperature of 12 °C.

The LAI of the treatment approximating commercial practice was simulated for the period when the canopy was expanding for all years. In order to obtain agreement with measured values it was necessary to vary the initial LAI at 14 days as a function of SOILN thus:

$$\text{Initial LAI} = 0.0004\ (10 - 0.07\ \text{SOILN})$$

The comparison of estimated and measured LAI is shown in Fig. 3.

In order to simulate the LAI of a crop for the whole season including the decline at the end of the season, it was necessary to assume that LAI did not increase between 120 and 140 days from sowing and that leaves of cotton are shed

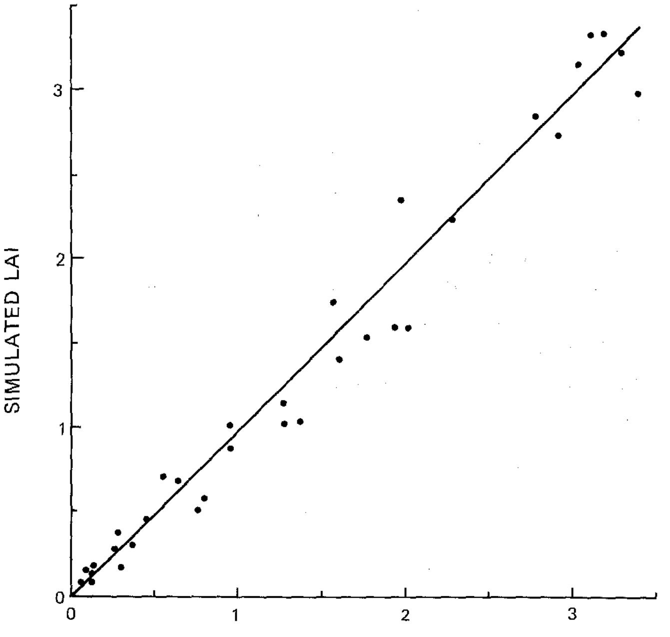

Fig. 3. Comparison of measured and simulated LAI when the canopy was expanding in the experimental treatment representing commercial practice

60 days after their appearance. From 140 days onwards decrease in LAI is simulated by subtracting the increment of 60 days previously.

To simulate LAI of crops which experienced greater stress than those used to derive equation (2), it was assumed LAI did not increase if the calculated LWP was less than −2.4 MPa, the value at which Grimes and Yamada (1982) found vegetative growth stopped.

Yield

The nitrogen uptake and leaf area functions were included in the water balance model, which was then run again for each of the 124 treatment combinations. Leaf area was generated and nitrogen uptake estimated for treatments on which they were not measured. During these runs the number of days were counted for each treatment on which the stress exceeded a certain threshold. In the absence of the abrupt closure of stomata and decrease in photosynthesis displayed by soybeans and used successfully to define a stress day, a variety of thresholds was tried. These included soil water deficits in the range 55% to 75%, and 80 mm to 110 mm, and LWP in the range −1.5 MPa to −2.7 MPa.

Stress days were summed for the following periods:

51– 80 days from sowing – approximately 15 days either side of first flower,
81–110 days from sowing – peak flowering,
111–140 days from sowing – early boll maturation,
141–160 days from sowing – mid boll maturation.

When regressing yield on stress days the best fit was obtained with a stress threshold based on LWP of −1.8 MPa for days 51 to 80 and −2.4 MPa thereafter.

The resultant relationship was:

$$\text{YIELD} = a + b_1S_1 + b_2S_2 + b_3S_3 + b_4S_4 + b_5(S_3 + S_4)\text{NUP}^2 + b_6S_1(S_2 + S_3)\text{NUP} + b_7\text{WL} \times \text{NUP}^2 + b_8\text{NUP} \quad (4)$$

in which

YIELD is lint kg ha^{-1}
S_1 is days with LWP < -1.8 MPa between 51 and 80 days from sowing
S_2 is days with LWP < -2.4 MPa between 81 and 110 days from sowing
S_3 is days with LWP < -2.4 MPa between 111 and 140 days from sowing
S_4 is days with LWP < -2.4 MPa between 141 and 160 days from sowing
WL is days of waterlogging with deficit $<$ 25 mm up to 120 days from sowing
NUP nitrogen uptake, kg N ha^{-1}

The values of the coefficients fitted were

a 513.	b_1 − 9.21	b_5 − 0.000929
	b_2 − 18.79	b_6 − 0.01644
	b_3 − 16.11	b_7 − 0.000959
	b_4 − 3.61	b_8 + 11.85

The coefficient of determination (R^2) was 0.80 (n = 124). The residual mean square for the treatment means from regression was 13,912 (d.f. 115) compared with the pooled error mean square of 16,190 (d.f. 171) from analysis of variance of the replicated plots (Constable and Hearn 1981). Thus the deviations of individual treatments from the regression equation are not statistically significant. The equation is an adequate description of the effects of the experimental treatments on yield, taking into account waterlogging, water stress and nitrogen supply. As an alternative to a stress threshold, relative daily photosynthesis estimated from Fig. 2 (a) and Grimes and Yamada's function for vegetative growth, were integrated for each period; the stress threshold using LWP was statistically better than either.

Equation (4) implies, but does not of course prove, that nitrogen determined the yield potential of cotton for this variety in this environment and that water stress and waterlogging reduced the yield below the potential, a view consistent with that of Crowther (1934). The effect of nitrogen uptake was to increase yield potential by 11.9 kg lint per kg N. Water stress between 50 and 160 days from sowing reduced yield. The main effect increased from 9.2 kg lint per stress day before day 81 to 18.8 kg between days 81 and 110 and 16.1 kg between days 111 and 140 and fell to 3.6 kg after day 140. These effects were modified by N level and interactions between stress periods. The quadratic effect of N was negative and interacted with both late stress ($S_3 + S_4$, from 111 to 160 days) and days of waterlogging. Early stress (S_1, from 51 to 80 days) interacted with subsequent stress ($S_2 + S_3$, from 81 to 140 days) so that the effect of early stress was greater when followed by late stress, especially when N uptake was large. All the interaction terms involve nitrogen and their net result is that the response to nitrogen is reduced by both water stress and waterlogging, as shown in Fig. 4.

Waterlogging affected yield in two ways: it reduced the amount of nitrogen taken up by the crop (2) and it then decreased the use made by the crop of the

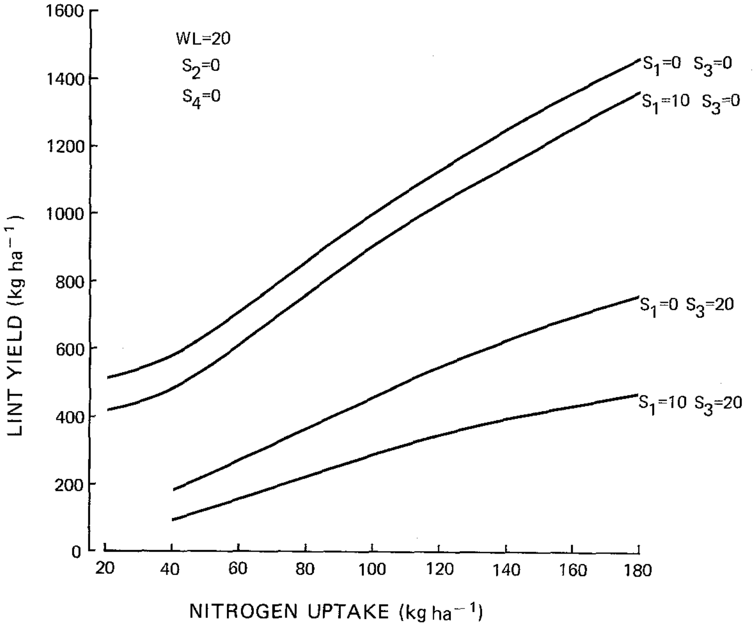

Fig. 4. The effect on lint yield of the interaction between early stress (51 to 80 days), late stress (111 to 140 days) and nitrogen uptake. A relationship expressed in equation (4)

nitrogen actually taken up (4). The first effect was to reduce uptake by 0.983 kg N ha^{-1} for each day of waterlogging; each kg reduction in N uptake in turn reduced yield by 11.9 kg lint. The second effect reduced yield by 21.5 kg lint for each day of waterlogging when uptake was 150 kg N. The total for both effects amounts to a reduction of 33.2 kg lint ha^{-1} for each day of waterlogging, equal to 1 bale (225 kg lint) ha^{-1} per week of waterlogging, or 2 to 3 bales ha^{-1} in an average season.

Simulation

The yield function was included in the water balance model. The model was now able to:

1) estimate daily soil water balance,
2) estimate daily minimum LWP (1),
3) estimate daily increase in LAI, thus generating LAI (3),
4) determine when to irrigate the crop on the basis of criterion given, restoring soil water balance to full capacity,
5) count days when the crop was stressed and waterlogged,
6) estimate nitrogen uptake at the end of the season as a function of initial soil nitrogen, fertilizer N and stress and waterlogged days (2), and
7) estimate yield at the end of the season as a function of nitrogen uptake and numbers of stress and waterlogged days (4).

Consequently yields could be simulated for any objectively defined irrigation scheduling method for any season given the following inputs:

1) daily rainfall,
2) initial soil nitrogen and fertilizer nitrogen,
3) available water holding capacity,
4) dates of sowing, first and last irrigation,
5) water supply in megalitres ha^{-1},
6) deficit at which crop is irrigated in mm or as % of current available water holding capacity.

The results of a number of simulations with 22 years of rainfall at the Narrabri Research Station and 95 years at Wee Waa are now reported. In these simulations the water balance is maintained through the winter. In this way the amount of water applied at pre-irrigation, which depends on the SWD at the time, can be estimated. The amount of irrigation is thus determined by the soil water stored at the end of the previous season and rainfall and evaporation during the winter.

Commercial Practice

A crop sown on 7th October and receiving 150 kg N ha^{-1} was simulated to represent commercial practice. The crop was irrigated at 50% deficit and no irrigation was applied before 16th December or after 6th March. The results are shown in Fig. 5. Despite the absence of water stress, simulated yields fluctuated between 800 and 1700 kg lint per hectare. This fluctuation in the simulated yields

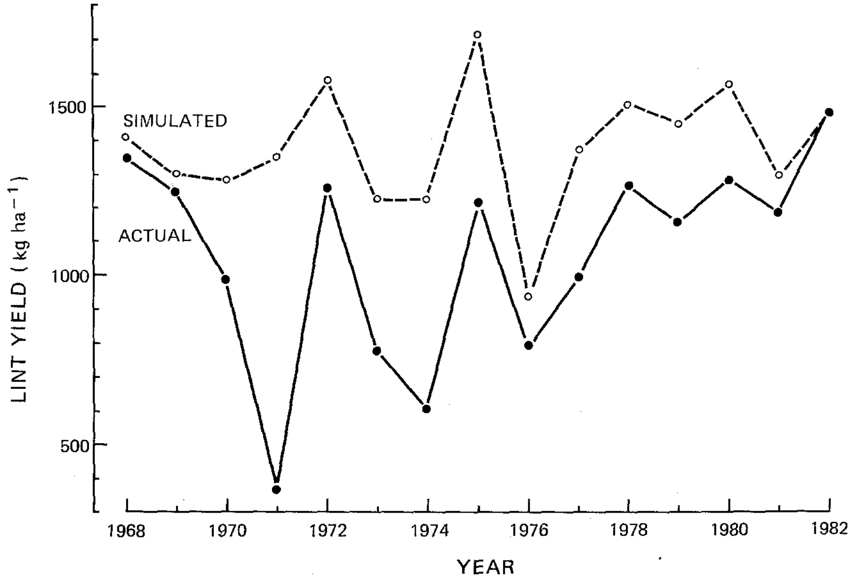

Fig. 5. Actual and simulated lint yields for commercial crops in the Namoi Valley Cotton Co-Operative from 1968 to 1982

reflected much of the variation in commercial yields and was associated with waterlogging. The major deviations were factors not accounted for in the water balance model: river flooding in 1971 and 1974 (giving rise to far more waterlogging than caused by local rainfall) and severe pest infestation in 1973. The practices described for this simulation are standard in the simulations subsequently reported.

Effect of Deficit at Irrigation

With other practices standard the deficit at which the crop was irrigated was increased from 40% to 80% by steps of 10%. The results of this simulation are given in Table 1. There was variation in the effect from year to year. Although on average irrigation at 50% deficit outyielded irrigation at 60%, at Wee Waa irrigation at 60% deficit outyielded irrigation at 50% in 28 of the 95 years.

Table 1. Effect of deficit at irrigation on mean simulated yield and water application

Deficit %	Research Station 1960 – 1982		Wee Waa 1884 – 1979	
	Water mm	Lint kg ha^{-1}	Water mm	Lint kg ha^{-1}
40	611	1296	651	1352
50	603	1410	626	1364
60	539	1219	595	1272
70	516	1022	562	1008
80	504	782	512	694

Even with reduced water supply (less than 8 Ml ha^{-1}) heaviest yields were obtained with irrigation at 50% deficit. Irrigating at a greater deficit in order to stretch a limited supply an average showed no advantage.

Changing the deficit at which the crop is irrigated during the course of the season was simulated. In most years at Wee Waa increasing the deficit from 50% to 60% between 91 and 120 days and decreasing it from 50% to 40% between 121 and 150 days increased yields without using any more water. The mean increase was 98 kg ha^{-1}.

First Crop Irrigation

The standard practice is for no irrigation before 70 days from sowing. This date was delayed by steps of 10 days from 60 days (6 Dec) to 110 days from sowing. For a crop to receive its first irrigation, the specific deficit had to be reached as well as the specified date. The results of the simulation are given in Table 2. On average, yields started to decline if the first irrigation was delayed beyond 60 days from sowing. However the effect varied from year to year depending on the rainfall pattern. When delayed from 60 until 70 days from sowing, yield decreased in only 51% of the years; in 32% of the years there was no effect while in 17% the yield increased. Corresponding figures for the delay from 70 until 80 days are a decrease in 57%, no effect in 22% and an increase in 21%.

Even with a reduced water supply, delaying the start of irrigation did not increase yields, heaviest yields were obtained by starting to irrigate at 60 days provided the deficit had reached 50%.

Last Irrigation

The standard practice is not be apply irrigation after 150 days from sowing (6th March for crops sown on 7th October). The last day of irrigation was delayed in the simulation in 10 day steps from 120 to 170 days from sowing. The means of the simulated water application and yields are given in Table 3. Standard commercial practice is 150 days. On average yields were increased by extending this period by 10 days. However yields were actually increased in only 62% of years; in 31% they were unaffected and in 7% decreased.

Supply of Irrigation Water

The standard allocation for this region is 6 megalitres per hectare. In the simulation 8 Ml was assumed in order to ensure that water supply was not limiting. If the supply is decreased, it will be exhausted progressively earlier in seasons of low rainfall but will last longer in wetter seasons. The amount of the supply was decreased from 8 Ml to 2 Ml in 1 Ml steps. The mean water application and lint yields from these simulations are found in Table 4.

As the supply was reduced, the number of years in which the supply was exhausted before the end of the season increased and consequently yield was reduced in those years. In some years however, yields were maintained even with

Table 2. Effect of timing of first crop irrigation on mean simulated yields and water application

First Irrigation	Research Station 1960 – 1982		Wee Waa 1884 – 1979	
Days from sowing	Water mm	Lint kg ha^{-1}	Water mm	Lint kg ha^{-1}
60	616	1425	636	1421
70	603	1410	626	1364
80	591	1350	606	1285
90	556	1259	564	1152
100	506	1065	533	948
110	456	919	478	702

Table 3. Effect of timing of last irrigation on mean simulated yields and water application

Last Water application	Wee Waa 1884 – 1979	
Days from sowing	Water mm	Lint kg ha^{-1}
120	489	767
130	547	1075
140	590	1245
150	626	1364
160	657	1417
170	678	1415

Table 4. Effect of supply of irrigation water on mean simulated yields and water application. In brackets are numbers of years when water supply was exhausted before the end of the season

Water Supply	Research Station 1960 – 1982		Wee Waa 1884 – 1979	
Ml ha^{-1}	Water mm	Lint kg ha^{-1}	Water mm	Lint kg ha^{-1}
2	205	303 (22)	214	275 (95)
3	311	551 (21)	320	426 (93)
4	420	695 (20)	413	577 (81)
5	511	1009 (14)	504	854 (65)
6	564	1219 (7)	580	1172 (27)
7	592	1370 (3)	612	1312 (12)
8	603	1410 (0)	626	1364 (0)

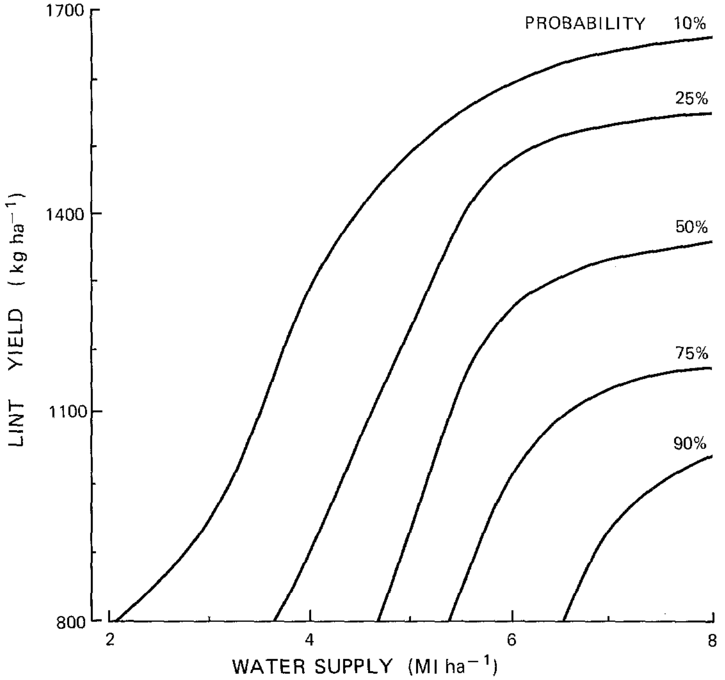

Fig. 6. Effect of irrigation water supply available in storage on simulated yield probability for cotton

small allocations. Therefore mean yield decreased and variation from year to year increased as the supply was reduced. Figure 6 shows the effect of supply on the probability of achieving various yields.

Nitrogen

The interaction of water supply with nitrogen fertilizer application was simulated. The results in Fig. 7 illustrate that less nitrogen is required when water supply is limited, and visa versa. The crop needs water to respond to N, a conclusion reached in many situations and well documented (Hearn 1979).

On average with adequate water simulated crops respond up to 200 kg ha^{-1}. However in some years less is needed as the simulated yields (kg lint ha^{-1}) for 1974 shows:

kg N ha^{-1}	Research Station	Wee Waa
0	746	768
50	930	1041
100	1157	1309
150	1228	1296
200	1233	1189

Net Returns

When simulating the effect of limited water supply, it was noted that as the supply was progressively reduced, average yield decreased because in an increasing number

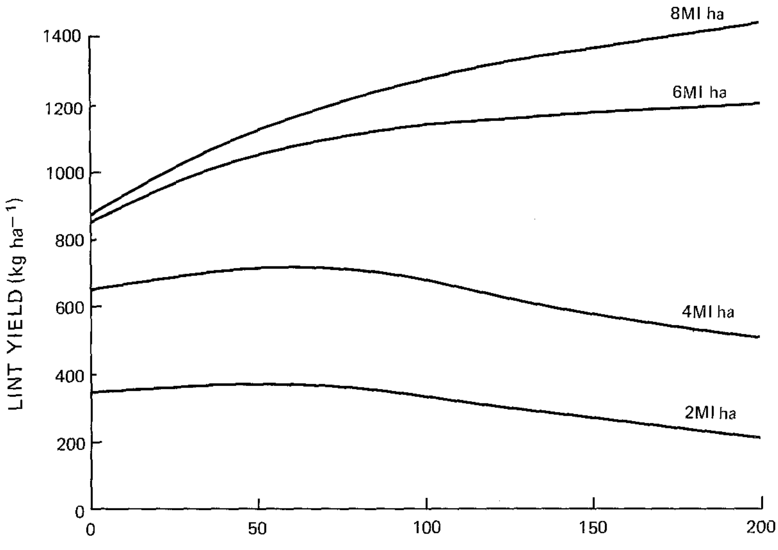

Fig. 7. Effect of irrigation water supply available in storage on simulated yield response of cotton to applied nitrogen meaned over years

of years the supply was exhausted before the end of the season. However when a grower has a fixed allocation of water from an off farm storage dam, reducing the amount of water per hectare means than he can grow a large area. He needs to know how far an increase in area of crop grown can compensate for the lighter average yields. This question was addressed by examining the returns per Ml of water in the simulation taking into account the cost of acquiring and developing land. Although the conclusions apply in detail to a particular economic situation, the principles that they illustrate are of general interest. Production costs were assumed to be $ 1125 per hectare excluding water but including interest payments on capital used to develop and purchase land as well as all materials consumed, labour and depreciation on machinery. Water was assumed to cost $ 2 Ml^{-1} pumped and lint to be sold for $ 1.4 kg^{-1}.

The mean net returns ($ Ml^{-1}) were:

Supply	Research Station	Wee Waa
8 Ml ha^{-1}	102.1	93.5
7 Ml ha^{-1}	108.1	96.5
6 Ml ha^{-1}	91.7	80.3
5 Ml ha^{-1}	52.1	8.2
4 Ml ha^{-1}	− 43.8	− 85.3

The returns fell sharply as the supply was reduced below 5 Ml ha^{-1}.

Figure 8 shows the variations expected in returns and the risks involved with different options. On the basis of these simulations there is little scope for increasing net returns per megalitre by reducing megalitres per hectare without risk of heavy losses in some years.

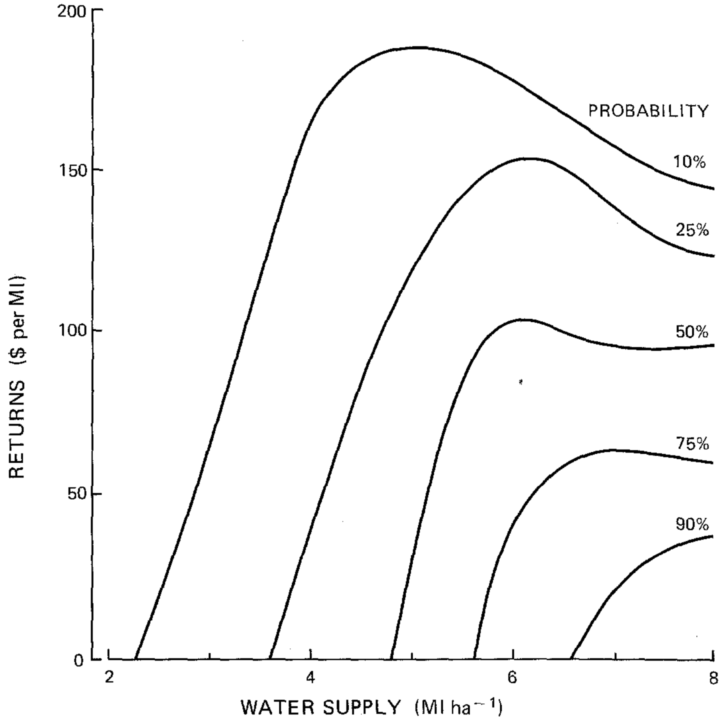

Fig. 8. Effect of irrigation water supply available in storage on probability of simulated net returns from cotton

In a sensitivity analysis the assumed production costs and the price for lint were varied by ±25% with the following net returns ($ Ml^{-1}):

Supply	Costs		Price	
Ml ha^{-1}	−25%	+25%	−25%	+25%
8	128.6	58.3	79.5	153.2
7	136.6	56.4	80.7	162.0
6	127.2	33.4	62.9	148.6

These results show that the conclusions reached do not depend heavily on the estimates of costs and prices. Within the range of ± 25%, maximum returns per Ml were obtained when 7 to 8 Ml ha^{-1} were available.

When the water level in an off farm storage dam is low at the time of sowing a grower may not receive a full allocation of water. There is the possibility either that the dam may be recharged by rainfall in the catchment before the crop requires irrigation or that rainfall on the crop may adequately supplement the limited supply. A grower's options include:

1) reducing the area sown so that the optimum allocation of 7 Ml ha^{-1} is available, or

2) sow a larger area with less than 7 Ml ha^{-1} available in the hope of receiving rainfall or an increased allocation, and

3) if option (2) is followed and the supply does not increase sufficiently, divide the area shown when the first irrigation is due and irrigate part and leave the rest as raingrown cotton.

These options were evaluated by simulation. The results show that whenever the supply to the area shown is less than 6 Ml per hectare, net return per Ml is greatest when the area irrigated is reduced in order to give a supply of 6 Ml per irrigated hectare leaving the rest of the crop as rain grown cotton. Risks are high and returns low if the crop is sown with less than 3 Ml available. Maximum returns per Ml of *water available at sowing* are likely to be obtained if the area sown is limited to give 6 or 7 Ml per hectare sown. If however the supply is subsequently increased the extra water cannot be used effectively and the returns per Ml of *extra water* will be low. For example we consider an enterprise with only 1000 Ml of water available at sowing time. By allowing 6 Ml ha^{-1}, 167 ha could be sown and irrigated, even if there is no subsequent increase in supply, giving on average a return over outlay of $ 165,000. With 3 Ml ha^{-1}, 333 ha could be grown and, if there is no increase in supply, half could be irrigated with 6 Ml ha^{-1} and half raingrown to give a return of average of $ 132,000 – clearly a less profitable option. However if the supply increases between sowing and first irrigation from 1000 Ml to 2000 Ml, with the 167 ha option only an additional 2 Ml ha^{-1} could be used raising the returns on average to $ 208,000. With the 333 ha option all the extra water could be used to give a return of $ 330,000 – clearly now the more profitable option.

Discussion and Conclusions

Although the subject of the study was water stress in relation to irrigation decision making, the effect of waterlogging associated with both rainfall and irrigation (days when SWD < 25 mm) has gained some prominence. This result emphasises that minimizing waterlogging is as important as minimizing water stress on this soil, a grey cracking clay. Although our yield reduction of 33 kg lint ha^{-1} per day of waterlogging cannot be directly compared with Hodgson's (1982) because his definition of a waterlogged day and integration over depth differed from ours, his data suggest the reduction could be much greater, Comparison of actual and simulated commercial yields in Fig. 4 provide partial validation, particularly in relation to the effect of waterlogging. Further validation is desirable but the model is location specific and can only be validated with independent local data sets which are not yet available.

The soil water deficit at which to irrigate cotton that is optimum for the particular soil and climate has been determined empirically by simulation. On average heaviest yields were obtained by irrigating at 50% deficit between 61 and 90 days from sowing, at 60% between 91 and 120 days and at 40% between 121 and 160 days. During the period 91–120 days, when a 60% deficit is preferable, the probability of rainfall is greatest and therefore the risk of stress is least and the risk of waterlogging greatest. After 120 days, when simulation gives heaviest yields with a 40% deficit, the crop will carry a heavy boll load and the root system will be unable to exploit deeper soil. The relative effect of these levels of stress on some physiological processes has been inferred from relationships discussed previously

Table 5. Optimum deficits for irrigation: vegetative growth, photosynthesis and boll growth

AGE days	Deficit for irrigation		Minimum LWP MPa	Relative % reduction		
	%	mm		Vegetative Growth	Photo-synthesis	Boll Growth
61 – 90	50	67 – 77	–18	45	12	Nil
91 – 120	60	93 – 108	–22	82	24	Nil
121 – 160	40	72	–22	82	24	Nil

and is presented in Table 5. Gross photosynthesis and fibre growth were relatively unaffected compared to stem elongation and leaf expansion. However two important aspects of development are not included: rate of production of fruiting sites and the survival (or in reverse the abscission or abortion) or fruit. Since vegetative growth was reduced relatively more than photosynthesis, stress at these deficits would increase the supply of photosynthates for fruit. Therefore fruit survival, which depends on assimilate supply, would not have been affected. Production of fruiting sites is unaffected until shortly before leaf expansion and stem elongation stop. It is postulated that before 90 days (just prior to peak flowering) the optimum deficit is one that permits leaf expansion to be maintained while after 90 days the optimum deficit is one that permits the production of fruiting sites to be maintained.

In California, where risk of rainfall prolonging waterlogging after irrigation is negligible and most soils are lighter, Grimes and Yamada (1982) obtained heaviest yields when LWP was allowed to decline to – 1.9 MPa before irrigation. By contrast with greater risk of rainfall our definition of stress to reduce yield is – 1.8 MPa up to 90 days and – 2.4 MPa thereafter. The optimum deficits for irrigation correspond to LWP values of – 1.8, and – 2.2 MPa (Table 5).

LWP could be used instead of percentage deficit as a basis for irrigation scheduling decisions both in simulation and in practice. However because LWP is determined by evaporative demand as well as soil water supply, inappropriate decisions could be made on cloudy days or exceptional days of high evaporative demand.

The optimum date of first irrigation (60 days after sowing) is earlier, and the optimum date of last irrigation (160 days from sowing) is later than practiced by most growers in the area but the water allocation required (7 Ml ha^{-1}) is in accordance with experience. With the last date of irrigation there are other considerations. Regrowth at the end of the season should be avoided as this interfers with defoliation. It is also desirable to deplete the soil water profile as much as possible by the end of the season in order to maximize the soil's capacity to accept autumn and winter rainfall and thus reduce both delays to picking and risk of damage to soil structure during subsequent land preparation. It is unwise to sow with less than 3 Ml available ha^{-1}.

Some of the conclusions from the simulation are counter-intuitive. For example when the water supply was less than 7 Ml ha^{-1}, there was no advantage in delaying irrigation either at the start of the season or by irrigating at a greater deficit. These empirically determined optimum practices for various aspects of irrigation are compromises in decision making between reducing the risk of water stress and reducing the risk of waterlogging consequent upon irrigation. These practices are those that, on average, perform best either in terms of yield or net returns. It is necessary to distinguish between these long term optimum practices and those that are optimum for a specific season. The results of these simulations show that there is no one set of practices that is always best for every season. For each practice there is a proportion of seasons in which an alternative performs better than the long term optimum.

The optimum strategy in terms of the area to crop given a constant water supply in the face of variable rainfall has been determined by simulation and the question of an occasional short fall in supply has been addressed. However further analysis is required to take into account the probability of variation in supply as an input to the water balance yield model.

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Appendix I. Range of Values of Variances in Regressions

Equation 1.	*For LWP*
AGE	53 to 153 days from sowing
EO	2.9 to 8.9 mm
SW	0 to 98.9%
Equation 2.	*For NUP*
FERTN	0 to 150 kg ha^{-1}
STRDAY	0 to 15 days with deficit > 70%
WL	6 to 47 days with deficit < 25 mm
Equation 3.	*For LAI Increase*
LAI	0.018 to 4.89
SOILN	51 to 86 kg ha^{-1}
WL	0 to 10% of days with deficit < 25 mm
NONSTR	11 to 100% of days with deficit < 55%
NUP	51 to 181 kg ha^{-1}
Equation 4.	*For Yield*
S_1	0 to 22 days LWP < – 1.8 MPa
S_2	0 to 8 days LWP < – 2.4 MPa
S_3	0 to 12 days LWP < – 2.4 MPa
S_4	0 to 19 days LWP < – 2.4 MPa
WL	6 to 54 days with deficit < 25 mm
NUP	10 to 161 kg ha^{-1}

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