MODELLING THE INFLUENCE OF FLOOD IRRIGATION ON WHEAT YIELDS IN CANTERBURY

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ABSTRACT

The ability of four models to describe the response of grain yield to flood irrigation of October sown wheat crops was evaluated. The models were:

1) The Effective Evapotranspiration model
2) The Actual Evapotranspiration model
3) The Drought Day model
4) The Phasic Actual Deficit (Jensen) model

The Effective ET model is based on the concept of a potential soil moisture deficit whereas the other three models are based on estimates of an actual soil moisture deficit. The Drought Day model assumed that growth stopped when the soil moisture deficit was greater than 75% of the plant available water. Potential evapotranspiration, adjusted for crop cover, was calculated daily using the Penman formula. The timing of the different stages of development required for the phasic model was based on elapsed photothermal time from sowing.

The Effective ET and Actual ET models both described nearly 80% of the variation in yields. The response of grain yield was 12 kg/ha per mm of irrigation applied when needed. The drought Day model described 70% of the variation in yield and showed grain yield to increase by 38 kg/ha per day of growth. The Jensen model described 80% of the variation in yield but the sensitivity of different developmental phases as indicated by the magnitude of the regression coefficients did not agree with more direct experimental evidence.

It was concluded that non-phasic models based on estimates of effective or actual ET can adequately describe the response of wheat grain yield to flood irrigation in Canterbury.

Additional Key Words: Evapotranspiration, photothermal time, potential deficit model, actual deficit model, phasic actual deficit model

INTRODUCTION

Experiments to determine an optimum irrigation regime for cereals in Canterbury have typically evaluated the yield response to two levels of irrigation. Recommendations to farmers from such experiments state the likely number of irrigations required by a crop in an average season and the phase of development and approximate date at which the water is required. No information is derived on the likely response of yield to each mm of water applied. A knowledge of the phases of development when irrigation is needed and the likely response of crop yields to irrigation is essential for both irrigation planners and farm managers. Such information can be derived from existing experiments by fitting models which describe the crop response to irrigation. A model is a set of equations describing a physical system and usually requires simplifying assumptions to be made. Researchers both overseas (e.g. Penman, 1962; French and Legg, 1979; Hanks and Rasmussen, 1982) and locally (e.g. Drewitt and Rickard, 1971) have shown that simple models incorporating rain, irrigation and estimates of evapotranspiration (ET) can adequately describe the response of cereal yields to irrigation. Four models which appeared to be promising were selected from previously published work and fitted to wheat yields recorded in irrigation experiments in Canterbury. Each model requires rain, irrigation and estimates of ET but the models differ in how the drought experienced by the crop is quantified.

The objectives of the study were:

1. To determine precisely the response of wheat grain yield to irrigation.
2. To examine whether the response of yield to irrigation depends on the phenological stage when irrigation is applied.
3. To test the suitability of four irrigation-yield response models for use in Canterbury.

EXPERIMENTAL DETAILS

Four experiments by Carter and Drewitt (pers. comm.) at Winchmore Irrigation Research Station to study the response of wheat (*Triticum aestivum* cv, 'Karamu') to irrigation were selected. The crops were sown in Mid-October in consecutive seasons from 1977/78 on a Lismore stony silt loam. These experiments were selected for their

TABLE 1: Summary of rainfall and potential evapotranspiration (ETp) at Winchmore.

	October		November		December		January		Total		No. of irrigations (15% trt)
	Rain (mm)	ETp (mm)	Rain (mm)	ETp (mm)	Rain (mm)	ETp (mm)	Rain (mm)	ETp (mm)	Rain (mm)	ETp (mm)	
1977/78	23	120	24	140	73	152	51	159	171	567	4
1978/79	91	106	36	141	124	128	39	166	290	541	2
1979/80	136	87	67	117	49	163	125	142	377	509	2
1980/81	47	75	118	72	50	128	33	127	248	402	3
Average 1968-80	62	100	65	117	62	138	68	139	257	494	

similar maximum yields (about 4 t/ha) for the treatments receiving the highest level of irrigation. Each experiment included a dryland treatment and two levels of irrigation applied when the moisture content of the top 150 mm of soil was 10% and 15% by weight. This corresponds to the laboratory-determined wilting point and to 25% of the available water. The experimental areas used during 1977/78 to 1979/80 had previously been in pasture for at least three years. The 1980/81 site grew a cereal crop in the previous year after being in pasture from 1976/77. Each crop received 240 kg/ha superphosphate and 120 kg/ha ammonium sulphate at sowing.

There was one anomaly in the experiment sown in 1978/79. The treatment irrigated at 10% soil moisture, which received one irrigation, yielded less than the dryland treatment of the same experiment. The experimental notes gave no clue as to the reason for this lower yield.

Table 1 gives monthly values of rainfall, potential evapotranspiration (ETp) calculated using the Penman formula (French and Legg, 1979) and the number of irrigations received by the treatments irrigated at 15% soil moisture. The rainfall received during October and November of 1977 was less than 40% of the 13 year average resulting in low yields for dryland crops. More than twice the average monthly rainfall was received in October 1979 and January 1980 resulting in small responses to irrigation during that season. The rainfall received during 1980/81 was close to the average but ETp was only 80% of the 13 year average.

THE MODELS

All four models assume that a maximum depth of water can be stored in the soil and used for plant growth. At the time of sowing, the soil water store is full. Water is taken from the soil store by evapotranspiration and the soil store is replenished by rainfall and irrigation. When rainfall and irrigation exceed the capacity of the soil store, the excess water drains away. The important features of the models are summarized in Table 2.

The Effective Potential Evapotranspiration model was first proposed by Penman (1952) and is based on the concept of a potential soil moisture deficit. The severity of

TABLE 2: Important features of the four models.

Model	Potential ET (ETp)	Size of soil store	Rules	Predictor
Effective Potential ET	Corrected for ground cover (ETm)	To be determined	Growth occurs at the maximum rate whenever there is water available in the soil store and stops when the store is empty.	Total effective ET
Actual ET	Corrected for ground cover and level of soil store (ETa)	90 mm	Growth occurs at the maximum rate until half the water is used. The rate of growth then declines linearly to zero when the store is empty.	Total actual ET
Drought Day	Corrected for ground cover and level of soil store (ETa)	90 mm	A drought day occurs when the soil water store is more than 75% depleted. Growth stops on a drought day but otherwise occurs at the maximum rate.	No. of drought days
Phasic Actual ET	Corrected for ground cover and level of soil store (ETa)	90 mm	As for the Actual ET model	Ratio of ETa/ETm during each phase

drought experienced by the crop is derived from the maximum difference between the total potential ET (adjusted for crop cover) and total rainfall plus irrigation received between sowing and maturity. Variations of this model have been used successfully in England (e.g. Gallagher *et al.*, 1983) to describe the response of crop yields to irrigation.

The Actual Evapotranspiration model is based on estimates of an actual soil moisture deficit. Actual ET is calculated by correcting the potential ET for both ground cover and soil water content. This model has been used successfully in the United States by, amongst others, Hanks *et al.* (1969) and Hanks and Rasmussen (1982).

The Drought Day model is also based on estimates of an actual soil moisture deficit and relates the grain yield to the number of days during which the soil water content is below a threshold value and growth is assumed to have stopped. The model was used successfully by Rickard (1960) to describe the effect of drought on pasture and lucerne production at Winchmore.

The Phasic Actual Evapotranspiration model (Jensen model) allows stress during different phases of development to have a different effect on the final yield. The stress during each phase is determined as the ratio of the actual ET to the potential ET after adjustment for ground cover. This model was proposed by Jensen (1968) and has been used in the United States for wheat and corn.

Details of the form of the models, the method of fitting and results obtained are described in sequence below.

METHODS

The potential ET was calculated daily using the Penman formula and meteorological observations from Winchmore (N.Z. Meteorological Service Station H31883).

Maximum evapotranspiration (ETm) is the potential ET adjusted for crop cover. During early growth when ground cover is poor, the rate of evapotranspiration from an annual crop is dominated by evaporation direct from the soil. As plant cover increases, transpiration of water by the crop is the dominant component of ET provided there is an adequate supply of water in the rooting zone (Ritchie, 1972). In this study, adjustment for ground cover was made during three phases. During the first phase from sowing to emergence, ETm equalled the evaporation from a bare soil (Es) calculated using the two phase soil model of Ritchie (1972). At 50% ground cover, many annual row crops have a leaf area index of 2.5-3.0 at which actual ET equals ETp when soil water is non-limiting (Ritchie, 1972; Tanner and Jury, 1976). During the phase from emergence to 50% ground cover, ETm was calculated as the average of Es and ETp (French and Legg, 1979). From 50% ground cover onwards, ETm equalled ETp.

Estimation of the duration from sowing to emergence sowing to 50% ground cover and sowing to maturity was assumed to depend primarily on temperature. The thermal duration from sowing to emergence was assumed to be 80 degree-days above a base of two degrees (Gallagher *et al.*, 1983; Angus *et al.*, 1980). Ground cover was assumed to reach 50% after 500 degree-days from sowing above a base of zero degrees (Gallagher, pers. comm.; Willington, pers. comm.) and the duration from sowing to maturity was 900 photoperiod adjusted degree-days (Baird, 1985).

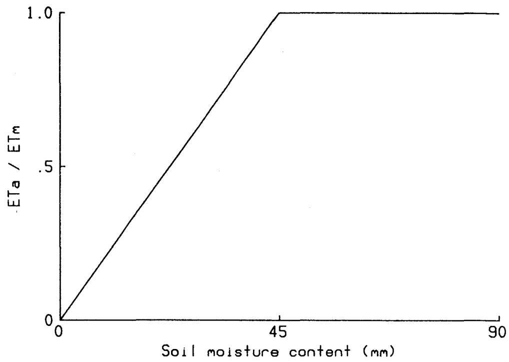

Figure 1: The relationship between relative ET (ETa/ETm) and the soil moisture content on the Lismore stony silt loam used to estimate ETa for the Actual ET, the Drought Day and the Jensen models.

To calculate actual ET it is necessary to know (i) the available water (AW) which is the maximum depth of water available for crop uptake within the rooting zone, (ii) the relationship between relative ET (ETa/ETm) and soil water content (SWC). The available water was considered to equal 90 mm (Stoker, 1982) and relative ET was related to the soil water content using a simple ratio function for $0 < SWC < 45$ and then ETa = ETm from 45 to 90 mm (Figure 1). This function adequately approximates the drying of soils if the relative ET falls below unity when half the AW has been used (Priestley and Taylor, 1972; Johns and Smith, 1975). The soil water content was calculated daily starting from the date of sowing.

$$SWC_t = SWC_{t-1} - ETa + R + I \qquad (1)$$

where

SWC = the soil water content (mm), the subscript representing the time in days from sowing

ETa = actual evapotranspiration (mm)

R = rainfall (mm)

I = irrigation (mm)

Flood irrigation was assumed to return the soil to field capacity (Hayman, pers. comm.).

The models are fitted by least squares regression and their ability to describe the response of wheat grain yield to irrigation is compared using the coefficient of determination adjusted for degrees of freedon (Ra^2). This statistic accounts for the number of predictors in each model and allows a more accurate comparison of the performance of the models than the unadjusted coefficient of determination (R^2). The Phasic Actual ET model does not contain an intercept and the sum of squares about the mean was subtracted from the regression sum of squares

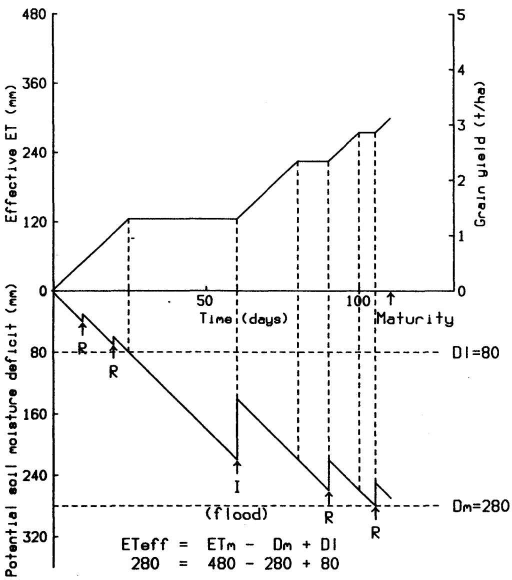

Figure 2: The relationship between the potential soil moisture deficit (D), effective ET (ETeff) and wheat grain yield (Y). ETeff accumulates until D exceeds the limiting deficit (Dl). Growth then stops, but restarts at the maximum rate after rain or irrigation until all the extra water is used.

and from the total sum of squares before calculation of Ra^2. This is the method used by the GENSTAT statistical package (Rothamsted Experimental Station, 1980).

THE EFFECTIVE POTENTIAL ET MODEL

The Concept of A Potential Deficit

The concept of a potential deficit was proposed by Penman (1952). At any time after sowing the potential deficit (D) equals the sum of the daily potential evapotranspiration minus the total depth of irrigation and rainfall.

$$D = \Sigma\, ETp - (\Sigma\, R + \Sigma\, I) + Ds \quad (2)$$

where

D = potential soil moisture deficit (mm)

ΣETp = potential evapotranspiration summed from sowing (mm)

ΣR = rainfall summed from sowing (mm)

ΣI = total depth of effective irrigation (mm)

Ds = the actual deficit at sowing, usually assumed to be zero

D is updated daily by adding the potential ET and substracting the depth of any rainfall or irrigation water received (Figure 2). Should total rainfall plus irrigation exceed Σ ETp, then D is set to zero. D cannot have a negative value and excess water is assumed to drain away. The potential deficit will rise as rainless days accumulate; then fall after a rainfall or irrigation event.

The Model

Penman (1962) postulated that there is a maximum level of D that will permit full growth. When D increases beyond this level, named the limiting deficit (D1), growth stops until further rain or irrigation water is received whereupon growth restarts again at the full rate until the extra water is used. Penman (1970a) commented that this division was obviously too drastic but it had the merits of being simple, meaningful, applicable to field results and it seemed to work. The limiting deficit represents the depth of water which can be stored in the soil and is freely available for growth. When D and Dm are increasing beyond D1, the soil is dry. The maximum depth of water which can be retained in a previously dry soil following rain or irrigation is D1 mm and for this reason D cannot fall below the current Dm by more than D1. As flood irrigation was assumed to return the soil to field capacity, each irrigation provided D1 mm of water. The maximum potential deficit (Dm) during the growing season is a measure of the severity of drought experienced by a crop (French and Legg, 1979).

The ET not used for plant growth is that occurring when D exceeds Dl and when D and Dm are increasing together. The total ineffective ET therefore equals Dm — Dl, the total effective ET (ETeff) is given by:

$$\Sigma ETeff = \Sigma\, ETm - (Dm - Dl) \text{ when } Dm > Dl$$
$$= \Sigma\, ETm \text{ when } Dm < Dl \quad (3)$$

where

ΣETeff = total effective evapotranspiration during growth (mm)

ΣETm = total maximum ET during growth which equals the potential ET adjusted for ground cover (mm)

Dm = maximum value of D during the season (mm)

Dl = limiting deficit (mm)

Penman (1970a) proposed that the yield is proportional to the effective ET.

$$Y = k * \Sigma\, ETeff + c \quad (4)$$

Calculation of the effective ET requires a value for Dl. As the limiting deficit was unknown for the Lismore soil, Dl was varied from 20 mm to 200 mm in steps of 2 mm. For each value, the effective ET was calculated, Equation (4) was then fitted by least squares regression and a coefficient of determination (Ra^2) obtained. The value selected for Dl was that which gave the highest Ra^2.

Results

The strongest correlation between Y and Σ ETeff was obtained when the limiting deficit equalled 80 mm (Figure 3). This represents 85% of the available water (AW) which was estimated as 90 mm in the top 100 cm of the Lismore soil from the work of Stoker (1982) with peas, pasture and barley. Other workers, both locally (e.g. Gallagher *et al.*, 1983) and in England (e.g. French and Legg, 1979; Day *et al.*, 1978) have found Dl to be about 50% of the AW for cereals and grain legumes but their method of deriving Dl differed from the approach used here. It is possible that a lower value for Dl would have

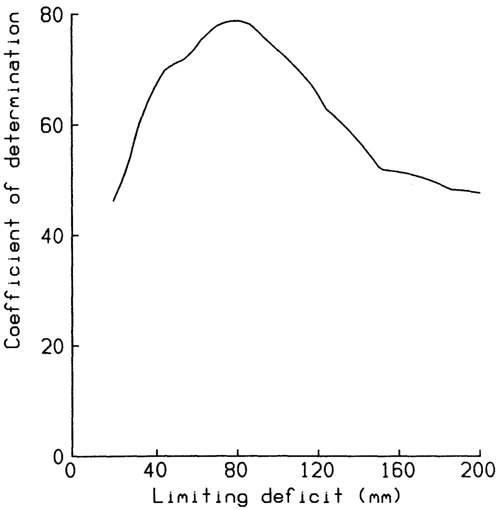

Figure 3: The percentage of yield variation explained by the Effective ET model over a range of values for Dl.

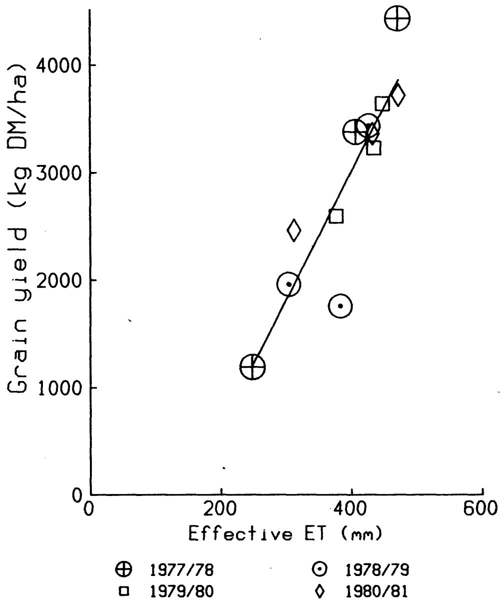

Figure 4: The relationship between wheat grain yield and Effective ET.

been obtained had the experiments included treatments where Dm was small. For example, when Dl equalled 80 mm, only one treatment from any of the four experiments had a value of Dm less than 80 mm.

The regression of yield on effective ET when Dl equalled 80 mm described 79% of the variation in yield (Figure 4). The response of grain yield to each mm of irrigation was 12 kg/ha, significant at the 1% level. This response was only half that recorded by Penman (1970b) on a sandy loam soil but Penman's crops yielded up to 5.5 t/ha and he was working in a more humid climate.

THE ACTUAL ET MODEL

The Model

This model assumes that the grain yield is a linear function of the total actual ET (Σ ETa) from the crop between sowing and maturity.

$$Y = g * \Sigma ETa + h \quad (5)$$

where

Y = grain yield (kg/ha)

ΣETa = the total actual ET between sowing and maturity (mm)

g = the response to irrigation used for growth (kg/ha/mm)

h = the ET necessary before any yield is achieved (mm)

Equation (5) was fitted by least squares regression to the data set and the best fit g and h obtained.

Results

The response to irrigation used for growth was 13 kg/ha/mm ($P < 0.01$) and the model described 77% of the variation in yield (Figure 5). These results were very similar to those for the Effective ET model and the similarity was probably due to the absence of well-watered treatments. The Actual ET model assumed that growth slowed when the actual deficit exceeded 45 mm whereas the Effective ET model assumed growth stopped at an actual deficit of 80 mm. Despite these different assumptions, the total actual ET was very similar to the total effective ET for each treatment. The response of 13 kg/ha/mm was similar to 10.2 kg/ha/mm and 11.8 kg/ha/mm reported by Stewart and Hagan (1973) for two varieties of wheat grown in Washington, USA.

THE DROUGHT DAY MODEL

The Model

The model is based on estimates of an actual soil moisture deficit and assumes that growth continues at the maximum rate until the soil water content falls below a threshold value. Growth then stops and drought days accumulate until rain or irrigation raises the SWC above the threshold. The grain yield of the crop is assumed to be a linear function of the number of drought days on which no growth occurred.

$$Y = Ym - b * \Sigma DD \quad (6)$$

where

Y = grain yield (kg/ha)

Ym = grain yield in the absence of drought (kg/ha)

b = grain yield loss (kg/ha) per day of drought

ΣDD = the number of days of drought

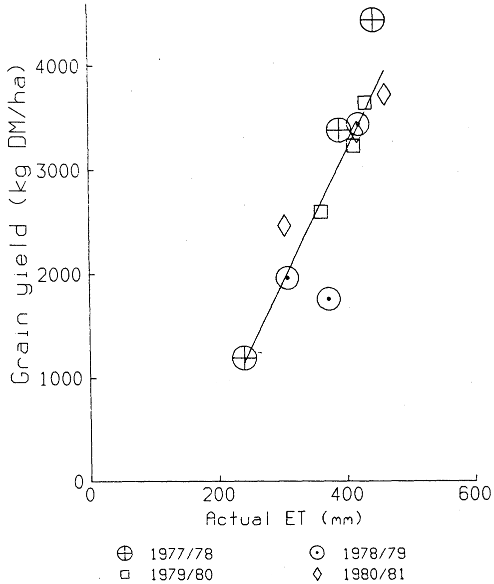

Figure 5: The relationship between wheat grain yield and Actual ET.

The definition of a drought day was based on the work of Rickard and Fitzgerald (1969) who used this model to describe the effects of drought on pasture yields at Winchmore. Rickard and Fitzgerald (1969) allowed the soil to dry to a deficit of 64 mm and a drought day occurred when the deficit exceeded 50 mm corresponding to wilting point. For this work, a drought day was defined as any day during which the actual soil moisture deficit exceeded 67 mm which equals 75% of the AW. This is in agreement with the work of Rickard and Fitzgerald when it is assumed that permanent wilting point corresponds to their maximum soil moisture deficit. Once the deficit exceeds 67 mm, drought days accumulate until the deficit becomes less than 67 mm following rain or irrigation. Small quantities of water, if insufficient to reduce the deficit below 67 mm were not immediately available for growth.

Equation (6) was fitted by least squares regression to the data set and the best fit Ym and b obtained.

Results

The Drought Day model described 71% of the variation in grain yield. The crop grain yield decreased by 38 kg/ha for each day of drought ($P < 0.01$)(Figure 6) and the maximum yield in the absence of drought was 3990 kg/ha. No published figures were found with which to compare this result.

THE PHASIC ACTUAL EVAPOTRANSPIRATION MODEL

The Model

The Jensen model relates relative yield to the relative ET in each phase of development from phase 1 through 3.

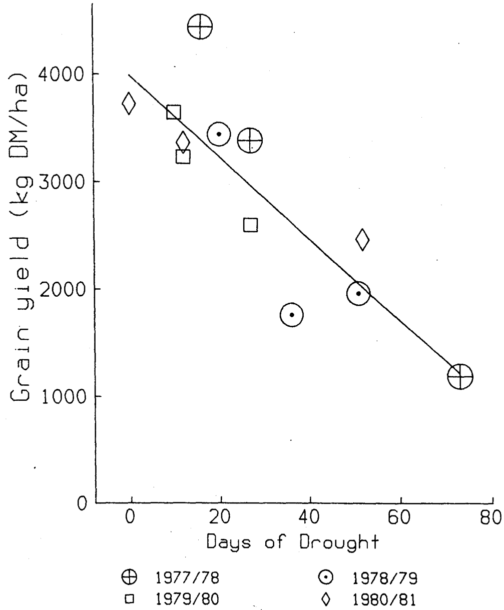

Figure 6: The relationship between wheat grain yield and the number of days of drought experienced by the crop.

$$\frac{Y}{Ym} = \left(\frac{\Sigma ETa_1}{\Sigma ETm_1}\right)^{L_1} * \left(\frac{\Sigma ETa_2}{\Sigma ETm_2}\right)^{L_2} * \left(\frac{\Sigma ETa_3}{\Sigma ETm_3}\right)^{L_3} \quad (7)$$

where

L_i = dimensionless exponents

Other terms are as previously defined

The magnitude of L_i indicates the sensitivity of the phase i to stress but, because L_i is an exponent, it is difficult to attach any precise physical meaning to its value.

As the well-watered treatments in each experiment accumulated small ET deficits and were therefore not 'fully' irrigated, Ym was calculated from the Actual ET model by setting ETa equal to ETm.

The three phases of development were:

1. Sowing to the end of tillering
2. End of tillering to anthesis
3. Anthesis to maturity

These three phases are often associated with the determination of the number of ears/unit ground area, the number of grains per ear, and the mean grain weight respectively. Estimation of the elapsed photothermal time to the end of each phase was based on the work of Langer (1979) who presented the approximate time and duration of physiological events, averaged over several cultivars, for wheat sown in Canterbury in early winter.

The Jensen model was fitted by least squares regression on a log transformation of Equation (7).

Results

The Jensen model described 76% of the variation in

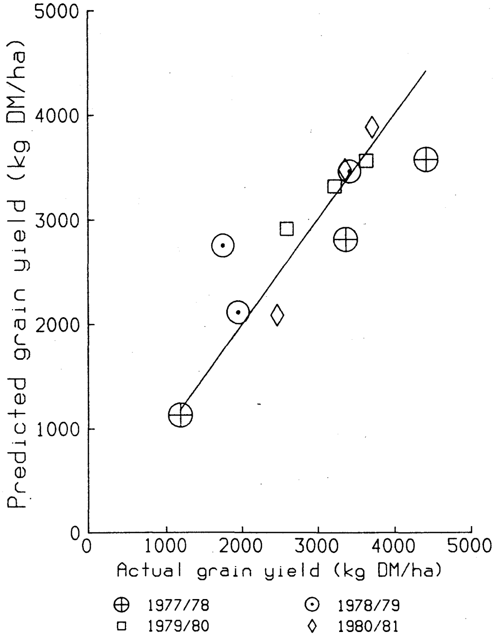

Figure 7: Predicted and actual wheat grain yields for the Jensen model. The line X = Y is drawn for comparison.

yield. Because the model includes three predictors, Figure 7 shows predicted yield plotted against actual yield. The values for L were

L_1 1.7
L_2 0.12
L_3 0.46

indicating that the phase from tillering to anthesis (i = 2) is the least sensitive to stress. Lorber and Haith (1981) fitted the Jensen model to corn grain yields using the same technique as in this work. The coefficients for two of the three phases indicated very low sensitivities to stress and were considered unreliable indicators of the sensitivity of the phases due to the small ET deficits incurred. The coefficients obtained here must also be treated with extreme caution. The experiments were not designed for the testing of phasic models and the range of intensities of stress in each phase was quite different. Only small ET deficits (< 20 mm) occurred during phase 1 and the magnitude of L for this phase proved very sensitive to small changes in the ET deficit. The standard errors associated with each coefficient could not be used for significance testing as the residuals from the regression failed a normality test.

DISCUSSION

The four models all described more than 70% of the variation in yields (Table 3). The response of yield per mm of irrigation and the coefficient of determination for the Effective ET and Actual ET models were very similar

TABLE 3: Summary of model fitting.

Model	Response	(s.e.)	R_a^2	n
Effective ET	12 kg/ha/mm	(1.8)	79	12
Actual ET	13 kg/ha/mm	(2.0)	77	12
Drought Day	38 kg/ha/day	(7.2)	71	12
Jensen	L_1 1.7 L_2 0.12 L_3 0.46		76	12

indicating that an estimate of the maximum potential soil moisture deficit adequately measures the drought experienced by a wheat crop. The limiting deficit of 80 mm for the Effective ET model represents 85% of the AW on the Lismore soil and requires some explanation. It may indicate that the AW is greater than 90 mm for wheat. It is certainly related to the assumption that growth stops rather than slows when Dm is increasing beyond D1 (Baird, 1985) and to the absence of treatments where Dm was less than D1 for values of D1 less than 80 mm. The Drought Day model described slightly less of the variation in yield than the other models but the response of 38 kg/ha/day of growth is consistent with the response of 12 kg/ha/mm for the Effective ET model. The average daily ETm from sowing to maturity was 3.1 mm which when multiplied by 12 kg/ha/mm gives a yield loss of 37 kg/ha/day.

The coefficients for the Jensen model implied sensitivities of the different phases to drought which do not conform with more direct experimental evidence. In particular the implied low sensitivity to drought of the phase from the end of tillering to anthesis disagrees with the results of many experiments (e.g. Drewitt and Rickard, 1971; Dougherty *et al.*, 1974). The coefficients proved sensitive to small changes in ET deficits in each phase and further work in this study (Baird, 1985) showed the coefficients to vary erratically with sowing date.

CONCLUSIONS

1. **Response to irrigation**

   The response of wheat yield was 12-13 kg/ha per mm of irrigation (or 3% for every 10 mm of irrigation) used for growth by crops whose maximum yields in the absence of drought was 3.5-4.0 t/ha. This is equivalent to a decrease in yield of 38 kg/ha (or 1% of a well irrigated yield) for each day of growth lost to drought.

2. **Timing of Irrigation**

   The soil moisture deficit at which to irrigate was not clearly defined but is likely to be when between 50% and 90% of the available water has been used. The analysis did not support the existence of moisture sensitive periods when yield is particularly responsive to irrigation.

3. **Processes of yield reduction**

   All four models described the effect of drought on grain yield equally well indicating that standard field growth-irrigation trials cannot be used to discriminate the processes of plant yield reduction due to water stress.

4. **Design of Experiments**

This work has clearly shown the need for a fully irrigated treatment in this type of experiment for which D never exceeds the limit at which yield is affected by drought.

Control over stress levels is essential in experiments designed to provide data to be used for fitting models such as Equation (7) which consider the timing of moisture stress on observed decreases in yield.

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