Interaction of the El Niño Southern Oscillation and Greenhouse Enhancement and its Implications for Australian Wheat Yields in 2060

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ABSTRACT

The usefulness of the Southern Oscillation Index (SOI) as a predictor of wheat yields in Australia has been assessed using historical records. Correlations between wheat yields and SOI were found to be most reliable in Queensland (r=.60) and less so in other states, particularly in South Australia (r=.24). The best method of using SOI values for predicting wheat yields varies from state to state. In general, it is most useful in regions that experience a summer rainfall peak (Qld and northern NSW) which replenishes the soil moisture store for winter cereal crops and is least useful for regions that experience winter rainfall peaks (WA, SA, Vic. and southern NSW). Predictions of average temperature, rainfall and evaporation hae been made for the different regions in the year 2060 under enhanced greenhouse conditions. A model of the wheat crop, which incorporates photosynthetic responses to atmospheric [CO_2], temperature and soil moisture, predicts significant changes in wheat yield from present conditions in 2060. Deleterious effects can be reduced by judicious selection of alternative cultivars.

INTRODUCTION

Two important factors that will influence yield variability of wheat crops in the 21st century, in Australia, are the El Niño Southern Oscillation Effect (ENSO) and greenhouse enhancement conditions resulting from emissions of greenhouse gases. The state of ENSO is represented by the Southern Oscillation Index (SOI). The results of correlation analyses (Rimmington and Nicholls 1993) of SOI and historical wheat yield data are presented. These show variable "skill" levels of SOI as a yield predictor across the Australian continent -- the result of the different climatic regions and weather systems involved. Likely climatic scenarios, in terms of equivalent atmospheric CO_2 concentration, temperature and rainfall, have been predicted using global circulation models (Pittock and Whetton 1990) The MUSIM/Wheat crop simulation model (Connor and Rimmington 1991; Handoko 1992) was modified to include a biochemical model of leaf photosynthesis and respiration. The model was used to simulate wheat yields in the Victorian Wimmera under present conditions and those likely to occur in the year 2060 (Wang *et al.* 1992). The results indicate that while yield reductions may occur when using current, local cultivars, the substitution of cultivars suited to warmer parts of the Australian wheatbelt may increase yields.

EL NIÑO SOUTHERN OSCILLATION

El Niño and La Niña (anti-El Niño) are the names given to positive and negative sea surface temperature anomalies (SSTA's) respectively, in the eastern equatorial Pacific Ocean on the west coast of South America. El Niño events are associated with abnormally low rainfall in Australia while La Niña events are associated with abnormally high rainfall (McBride and Nicholls 1983; Allan 1988; Nicholls 1989) (**Figure 1**). The inter-annual variation in SSTA's is correlated with the change in sea level air pressure differences between the eastern and western equatorial Pacific Ocean, known as the Southern Oscillation (Nicholls 1990). A possible explanation for the link between these two phenomena is the strengthening of the Walker Cell which circulates clockwise across the Pacific due during La Niña episodes, resulting in movement of moist air, eastward, toward the Australian continent and its weakening and break-up during El Niño events which blocks the movement of moist air (**Figure 2**) (Nicholls 1991). These two phenomena are often considered synonymously and are quantitatively represented as the normalised difference between sea level air pressure between Darwin (Australia) and Tahiti in the eastern Pacific multiplied by 10 -- the Southern Oscillation Index (SOI) (Troup 1965). SOI values between -10 and 10 (plus or minus one standard deviate) represent average conditions. When the SOI exceeds 10 a La Niña event is said to be under way and when it falls below -10 the condition is an El Niño event.

Changes between El Niño, La Niña and average conditions occur each year by the month of April (Rimmington & Nicholls 1993). For this reason the annual cycle in this paper is regarded as May to April rather than the calendar year.

MONTH	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
MEAN	0.0	-0.2	0.0	-0.2	-0.1	0.1	-0.1	-0.4	-0.1	-0.6	-0.6	-0.6
SD	10.26	9.93	9.93	9.91	10.06	10.00	10.05	10.03	10.14	10.11	10.14	10.39
SE	0.97	0.94	0.94	0.94	0.96	0.95	0.95	0.95	0.96	0.96	0.96	0.99
MAX	21.0	22.6	26.3	33.1	29.2	19.9	31.5	21.7	20.3	18.0	17.0	27.7
MIN	-38.8	-27.7	-21.0	-24.0	-20.0	-22.3	-30.0	-30.7	-31.4	-35.7	-27.7	-38.2
RANGE	59.8	50.3	47.3	57.1	49.2	42.2	61.5	52.4	51.7	53.7	44.7	**65.9**

Table 1. Summary of monthly SOI data for the period 1882 to 1992.

El Niño or La Niño events have occurred every 4.0±1.2 years since 1882 with the longest gap of 14 years between 1956-7 and 1969-70. The lowest annual average SOI value on record was -22.2 in 1982-83 while the highest (18.9) occurred in 1917-18 (**Table 1**). On a monthly basis, extreme positive and negative values of 33.1 and -38.8 occurred in August 1917 and May 1896, respectively. Within any annual cycle the amplitude of SOI varied from 4.8 in 1955-56 and 23.9 in 1904-05 (**Figure 1**). The probability distribution of monthly SOI values is shown in **Figure 3** and is not significantly different from a normal distribution ($p>0.19$).

When annual, average SOI values for May through April are classified into "dry" (SOI>10.0) "average" (-10.0≤SOI≤+10.0) and "wet" (SOI<-10.0) there are 9 (10%) "dry", 76 (80%) "average" and 10 (11%) "wet" years in the 95 years for which there is complete SOI data. When transitions between these classes for consecutive years (88 with complete data) are examined, a transition probability matrix may be obtained (**Table 2**). The probability of a "dry/wet" couple or "biennial cycle" (Ropelowski *et al.* 1992) is 25%, while that for the reverse is zero, although there was a 3.8% probability of a "wet/ave/dry" triplet. The probabilities of long "dry" or "wet" periods of low with "average" periods dominating (81.2% "ave-ave"). Transitional probabilities differed significantly ($p<.005$) from equal probability of outcomes.

	W	D	A
W	0.100	0.000	0.900
D	0.222	0.111	0.667
A	0.087	0.101	0.812

Table 2. Transition probability matrix for SOI classes.

Rainfall variability is a dominant factor affecting variation in wheat yields across the Australian wheatbelt (Connor and Rimmington, 1990) and this in turn determines the management strategies and tactics used in different climatic regions (Rimmington and Connor 1991). Any means of predicting the outcomes of different management strategies will benefit cereal growers. A general framework, comprising a simulation model run on a supercomputer to generate a database of yield exceedance probability curves that, in turn, can be accessed on a microcomputer, has been proposed (Rimmington and Connor, 1990) and is under development (**Figure 4**) ('Cereal Game' Hofflin, Rimmington, Hawkins and Connor unpublished). This system uses a simulation model and a weather generator (Geng *et al.* 1988) and is described more fully in Connor and Rimmington (1991).

There is scope for the improvement of such models by explicitly accounting for the effects of ENSO upon crop yields. Already, Dudley and Hearn (1993) have shown for irrigated cotton, that crop management outcomes improve when ENSO is taken into account. To this end, correlations between wheat yields and SOI were sought for the various and for the nation (Rimmington and Nicholls, 1993). The analysis showed that SOI values for the current cropping season were of limited value, especially outside the summer rainfall zone of northern NSW and southern Qld. However, trends in SOI in successive years were used to obtain correlation coefficients of up to 60%. Both the best predictor and the level of correlation varied between states (**Figure 5**). Such predictors are not good enough to be used alone but have value when combined with other methods.

GREENHOUSE ENHANCEMENT

The combined effects of SOI and greenhouse enhancement upon cereal crop yield is of interest. Under various scenarios of greenhouse enhancement, the future behaviour of ENSO is uncertain (Pittock 1991). When an ocean circulation model was coupled to a general circulation model for the atmosphere, results were consistent with the observed behaviour of the southern oscillation (CSIRO 1990).

Since the beginning of the industrial revolution, atmospheric concentrations of CO_2 and other "greenhouse" gases have increased by an amount radiatively equivalent to 50%. CO_2 concentration has increased from 280 to 350 μmol mol^{-1} (Houghton *et al.* 1990). The global average CO_2 concentration is expected to reach twice the pre-industrial revolution levels (560 μmol mol^{-1}) by 2060 with average global surface warming by 1.5°C above present temperatures. Global surface warming is unlikely to be uniform and the CSIRO4 global climate model (Pittock and Whetton 1990) predicts that the average temperature in Victoria, Australia could increase by between 1 and 3°C by about 2060. Rainfall for the same period is predicted to increase in summer and decrease in winter by up to 20% and 10%, respectively.

A simulation model of the growth, development, water-use and yield of the wheat crop (Connor and Rimmington 1991) was modified by replacing the simple light-use efficiency formula,

$$\frac{dW}{dt} = \varepsilon J - \Lambda \qquad \text{.......... 1}$$

where W is above-ground dry weight (g DW m^{-2}), ε is the light-use efficiency (g DW MJ^{-1}), J is the daily integral of canopy light interception (MJ m^{-2} day^{-1}) and Λ is the daily loss of dry matter (g DW m^{-2} day^{-1}), with

$$\frac{dW}{dt} = \alpha A_c f_w - \gamma W \qquad \text{.......... 2}$$

where α is conversion coefficient for moles of carbon to new dry matter,. A_c is the photosynthetic carbon assimilation rate for the canopy when water supply is not limiting, γ is the canopy maintenance coefficient, f_w is a factor which reduces canopy assimilation rate due to reduced canopy transpiration (T m H_2Om^{-2} day^{-1}) where

$$fw = \frac{T}{T'} \qquad \text{.......... 3}$$

$T = \min\{Tx, T'\}$ 4

and Tx is soil-moisture limited transpiration rate while T' is energy-limited (potential) transpiration rate. The canopy photosynthetic assimilation rate, A_c, is the integral of leaf photosynthesis rate, A_l, over canopy depth and over 24 hours. A_l is calculated with the biochemical leaf photosynthesis model of Farqhuar and von Caemmerer (1982) as parameterized by Wang *et al.* (1991). This has been validated against data from field gas-exchange measurements and from phytotron experiments (*Ibid.*).

The overall model which accounts for effects of atmospheric CO_2 concentration, temperature, incident solar radiation, soil moisture, cultivar characteristics, soil physical properties and sowing date, was tested against field data (Handoko 1992) and provided adequate predictions of above-ground dry weight (r^2=0.73 RMSE=55.4) final grain number (r^2=.98 RMSE=419.8) and potential yield levels.

Growth sensitivity to increased air temperature for different scenarios of CO_2 concentration and rainfall was assessed for the Victorian Wimmera. The average annual rainfall for Horsham, a major centre in the Wimmera, is about 450 mm, the mean daily maximum air temperature in December is 27.3°C and the mean daily minimum air temperature in July is 3.5°C. Average wheat yields for the Wimmera were about 1.7 t ha^{-1} between 1977 and 1988.

Initially two cultivars were chosen for this simulation study, Egret and Matong, which are grown in southern NSW and Victoria. Predictions of potential grain yield (t ha^{-1}) are presented (**Figure 6**) for two scenarios -- current conditions ($[CO_2]$=350 $\mu mol\ mol^{-1}$), and greenhouse enhanced conditions ($[CO_2]\equiv700$ $\mu mol\ mol^{-1}$ and +3°C). The simulations were repeated at 14 day intervals for sowing dates ranging from day 90 (March 31st) and day 210 (July 29th). Yield potential is depressed over most of the season for Egret and Matong, while it is increased above present yields for all three cultivars in UQ189. The reduction in yield potential by Egret and Matong can be explained by a reduction in growing season length (sowing to physiological maturity) (**Figure 7**) and, in particular for the vegetative growing period (sowing to anthesis) (**Figure 8**). The relative difference in growing season length is less in UQ189. This would lead to comparatively higher biomass and leaf area index at anthesis and, as a consequence, a higher yield potential.

When a range of temperature and rainfall scenarios are explored (**Figure 9**) it becomes obvious that Egret and Matong are much more sensitive to reductions an rainfall under higher temperatures than is UQ189. In fact, the latter exhibits an advantage of more than 50% over most of the range of conditions. Not only is UQ189 better suited to greenhouse enhanced temperatures, the implied differential in its water-use efficiency is superior to that of Egret or Matong.

CONCLUSIONS

The analysis of SOI as a possible predictor of wheat yields in Australia shows that it will prove more useful in the summer rainfall zone. The best predictive function varies from state to state with inter-seasonal trends in SOI proving to be more useful than within-season SOI values. The influence of SOI is through changes in rainfall. Thus rainfall distribution through the season and soil water-holding characteristics must be considered when interpreting ENSO effects. Predictions of wheat yield may be improved by future combination of SOI with western Pacific sea surface temperature anomalies (Russell 1990), rainfall indexes (Stephens *et al.* 1991) and satellite imagery (Rimmington and Connor 1990).

The analysis of greenhouse enhancement effects upon wheat yield show that yields of current, local cultivars may decrease due to shortening of the vegetative growing period and consequent lowering of yield potential. This effect increases the susceptibility of crops to lower rainfall such as will occur during an El Niño event. When the cultivar UQ189, which is suited to Queensland -- a warmer climate -- is substituted, higher yields are predicted in 2060 -- the result of a longer growing season. Higher water-use efficiency and better response to CO_2 "fertilization". are two possible explanations. It is uncertain whether the compensation of CO_2 enrichment for reduced water supply will be equally effective under the extremes of El Niño and La Niña and this remains a topic of study by our group.

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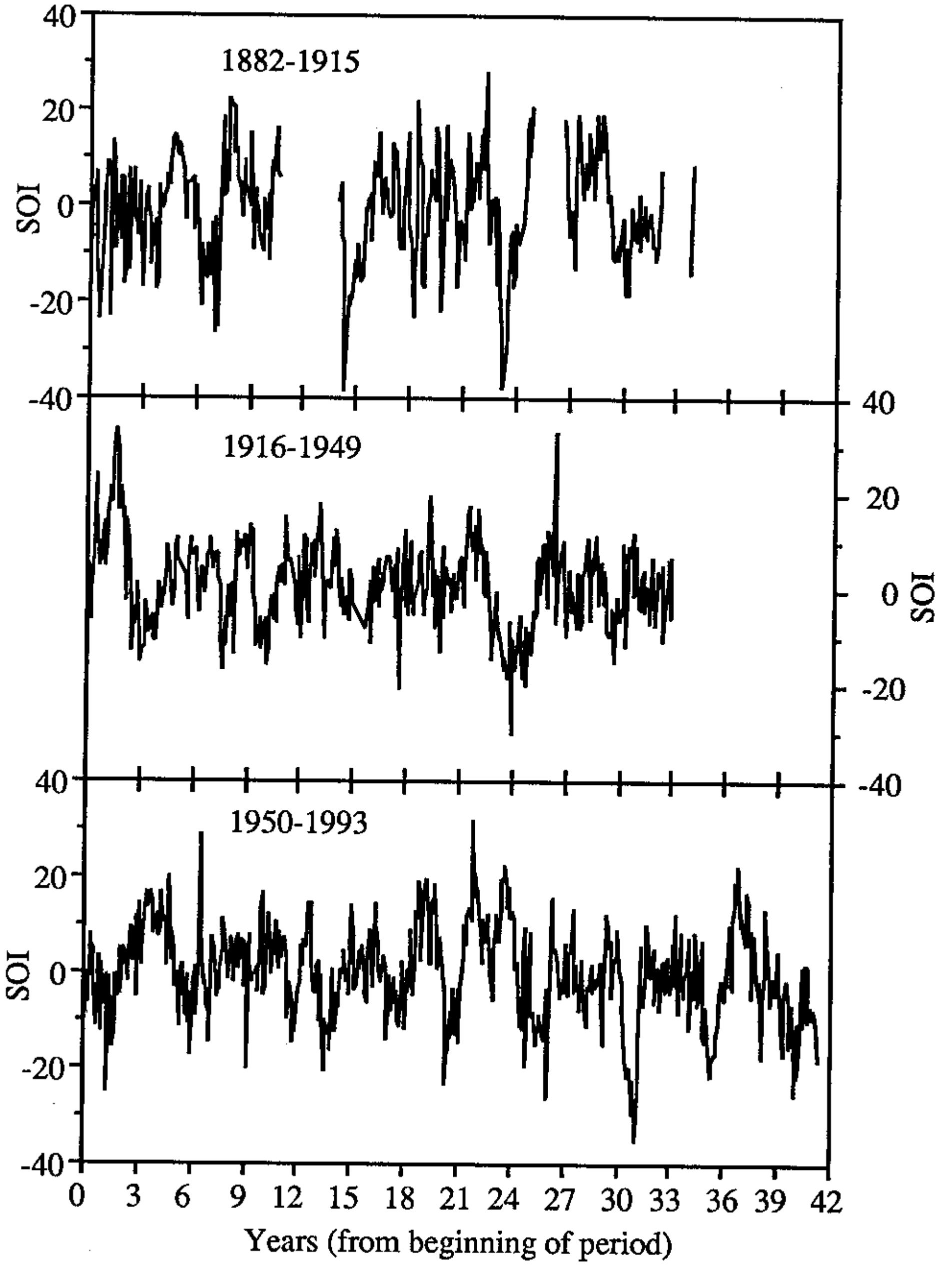
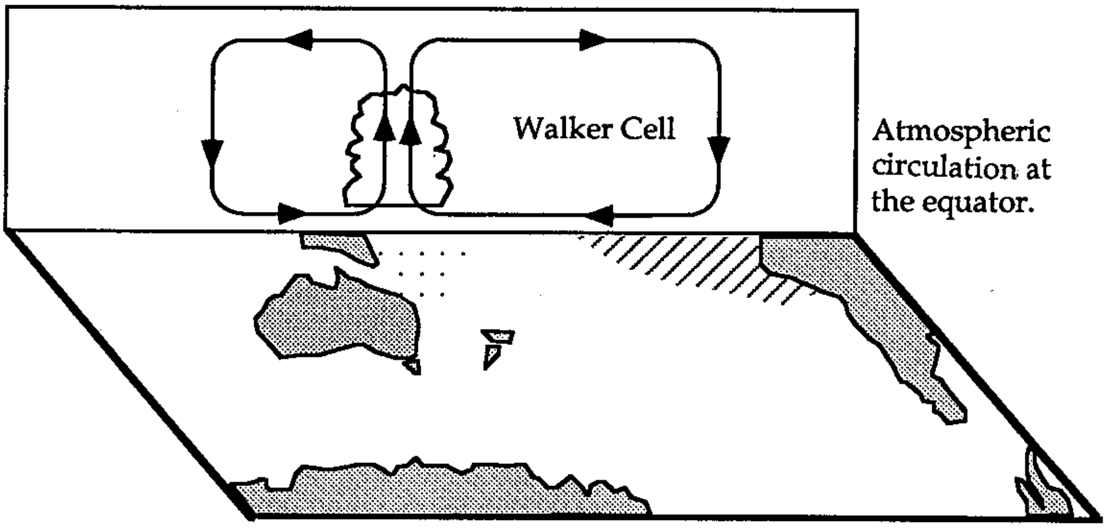
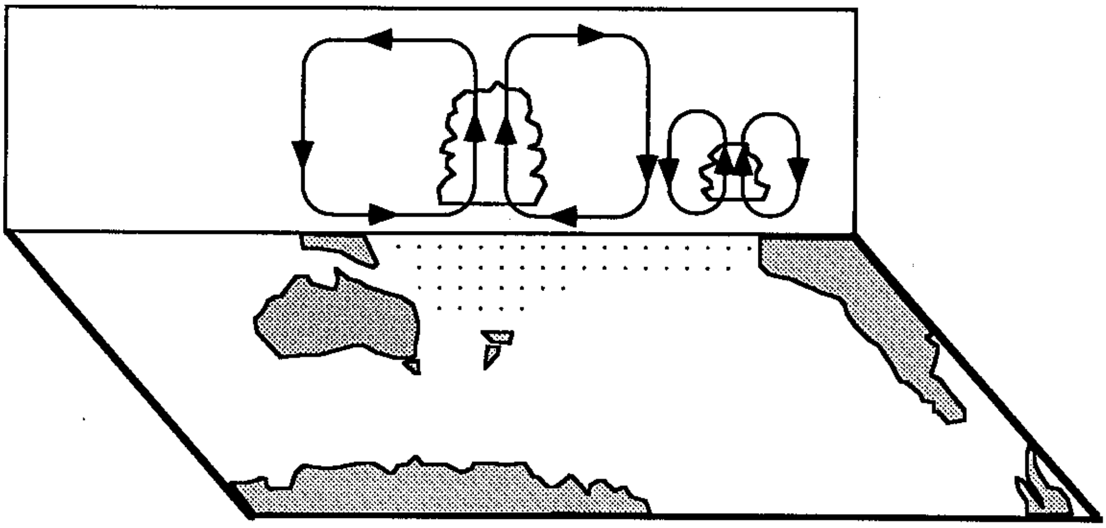


Figure 1. SOI values from 1882 to the present.



Typical La Niña (anti-El Niño) year with strong Walker cell circulation.



Typical El Niño year in which the Walker cell is fractured and weakened.

Warm Sea Surface Temperature Anomaly.

Cool Sea Surface Temperature Anomaly.

Figure 2. Relationship between atmospheric circulation and sea surface termpature anomalies during El Niño and La Niña events (BOM 1990).

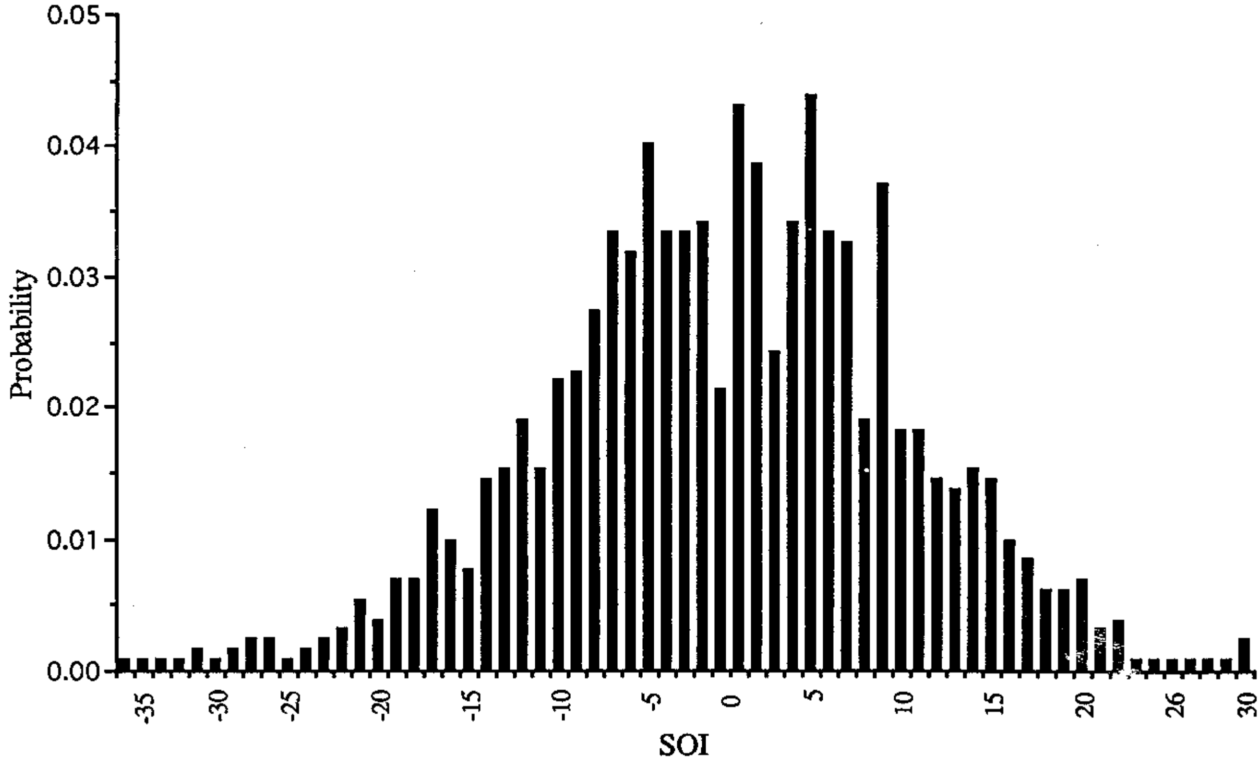


Figure 3. Probability of SOI values for the 1882-1993 period.

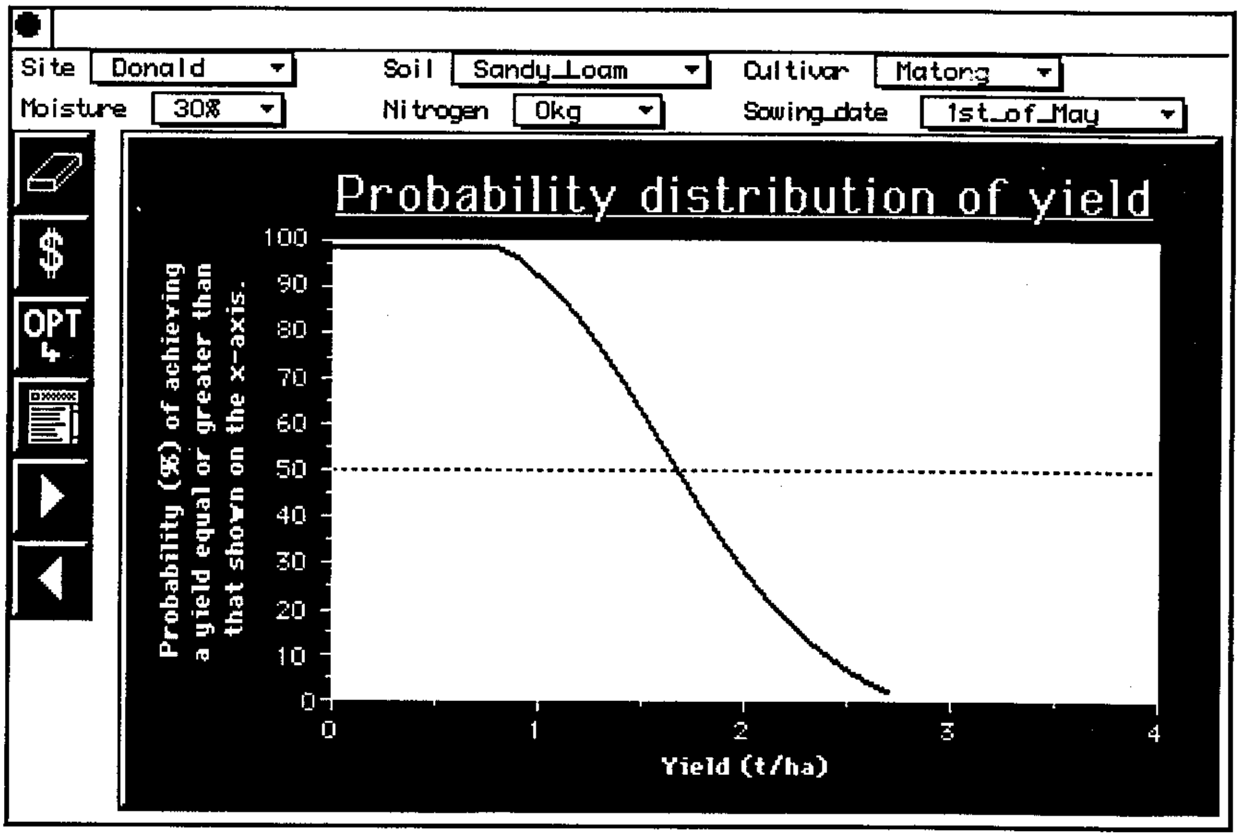


Figure 4. A screen from the Cereal Game (Hofflin, Rimmington, Hawkins and Connor unpublished).

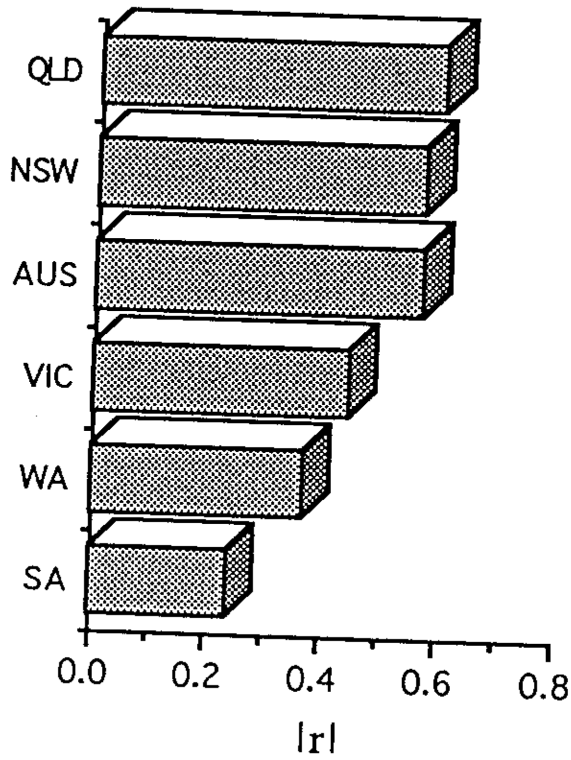


Figure 5. Highest, absolute correltation coefficients for detrended wheat yield and functions for within-season and previous-season, monthly SOI values, over the period 1948 to 1988 (Rimmington and Nicholls 1993).

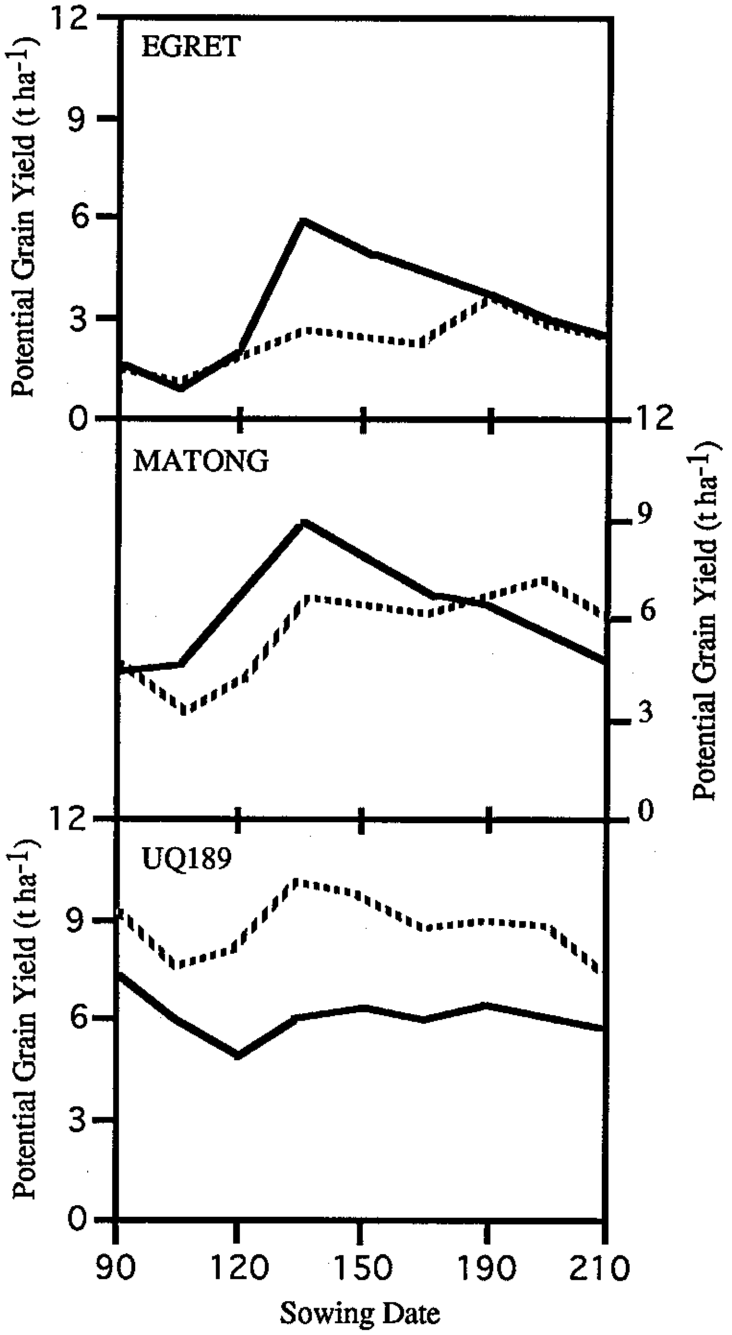


Figure 6. Simulated potential grain yield Tt ha^{-1}) for cultivars Egret, Matong and UQ189 under present conditions (———) and greenhouse enhanced conditions (············) (adapted from Wang *et al.* 1992).

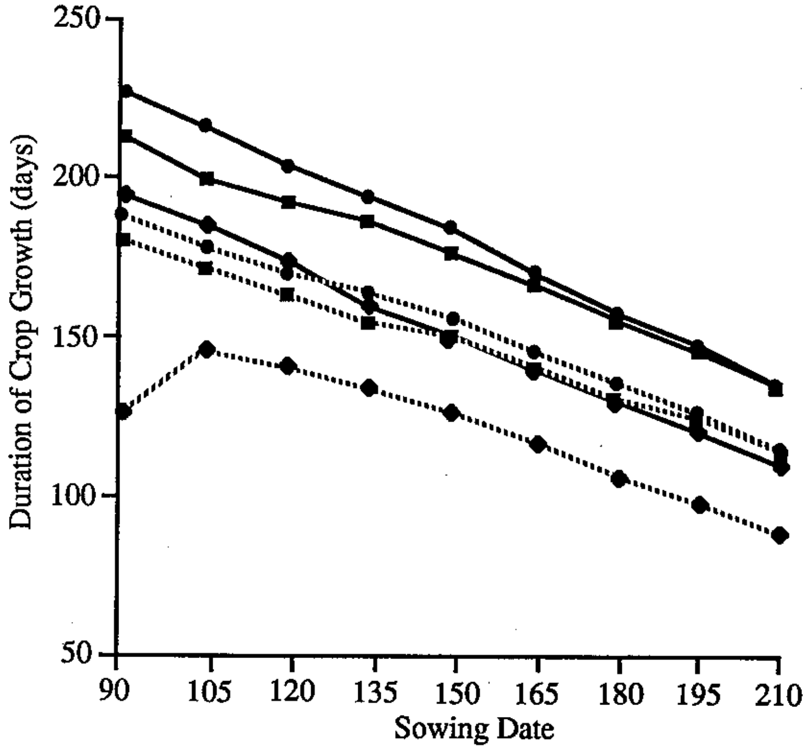


Figure 7. Predicted duration of crop growth (sowing to physiological maturity) for Egret (◆) Matong (■) and UQ189 (●) under present conditions (———) and greenhouse enhanced conditions (••••••••••) for sowing dates from 90 to 120 (days after Jan 1) (adapted from Wang *et al.* 1992).

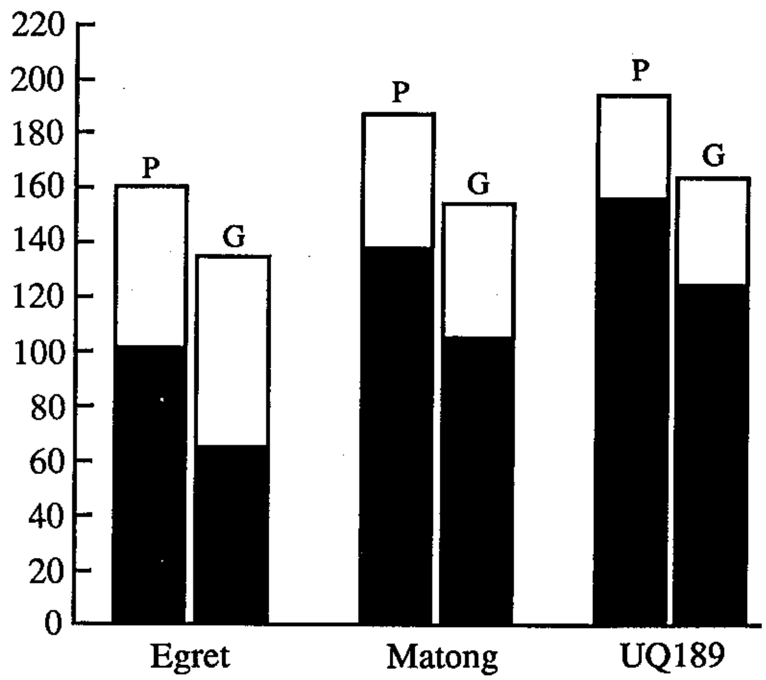


Figure 8. Predicted duration of crop growth from sowing to anthesis (■) and anthesis to physiological maturity (□) for present (P) and greenhouse enhanced (G) conditions for Egret, Matong and UQ189 sown on day 135 (adapted from Wang *et al.* 1992).

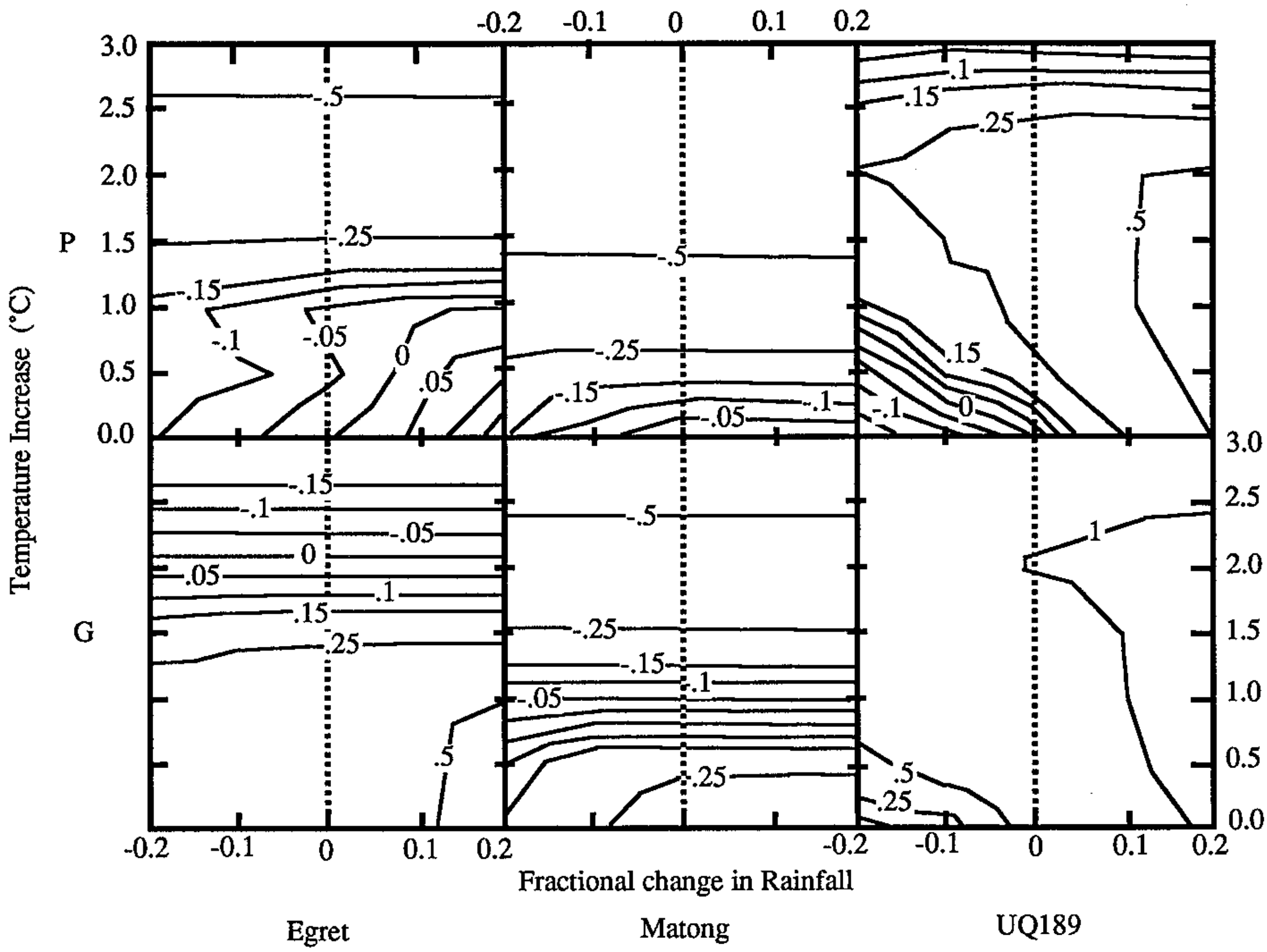


Figure 9. Predicted relative change in potential grain yield as a function of temperature increase (0 to 3°C) and fractional change in annual rainfall (-0.2 to 0.2) under the present (P) atmospheric CO_2 concentrationand under greenhouse enhanced (G) CO_2 concentration for the three cultivars: Egret, Matong and UQ189 (adapted from Wang *et al.* 1992).