Climatic Change and The Australian Wheat Crop

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ABSTRACT

The Australian wheat crop of 10 - 12 Mha is grown over a wide geographic area from 20 to 38 S and 118 to 150 E. This area provides wide ranges in the climatic factors of rainfall, radiation, temperature and photoperiod that determine the development, growth, and yield of the crop. The consistent feature of crop performance over this wide range is the small (mean = 1.25 t/ha) and variable (se = 0.23 t/ha) yield which reflects the same properties of the regional rainfall.

The variability of yield and the dominance of low rainfall to productivity make the assessment of climatic change difficult. In the study reported here, a simulation model of the wheat crop is used to assess the effect of climatic change on the productivity at two locations representative of large areas of production. The model is used to assess the separate and interacting effects of temperature increases up to 3 C and [CO_2] from 350 to 460 ppm. It is estimated that increase in [CO_2] would raise yield by 23 % but that with associated higher temperature, the net yield change would be of the order of -37 to -51%. The larger reduction occurring at sites of higher rainfall and higher yield. The model was also used to assess how modification to the phenological response of cultivars might be used to offset the effects of climatic change. These analyses suggest that it would be possible to maintain yield under the climatic regime (+3 C, 460 ppm [CO_2]) by adjusting the balance of vegetative growth periods before and after stem extension.

It is concluded that simulation models offer the only realistic way to assess the effects of climate change scenarios on crop response and cultivar design but that this should include a continuing commitment to their improvement so that, in particular, they capture the varied range of physiological responses of crops to [CO_2].

INTRODUCTION

The Australian wheat crop is grown over a wide geographic and hence climatic range. The unifying features are that it is grown in drought-prone areas, at small and variable yields, in large fields, on large farms, and often in rotation with other crops and with pastures that support livestock enterprises, dominantly sheep. The major part of the production is sold for export on the world market where prices received are also low and variable. The combined risk of low yield and low prices means that the emphasis in production is more on the curtailment of inputs and hence costs rather than on the maximisation of yield.

The currently promulgated scenario for induced climatic change in the Australian wheat zone by the year 2030 combines increase in average temperature by up to 3 C with greater summer (+20%) and smaller winter rainfall (-10%). Of the radiatively active gases that generate that result, the one of interest to crop production,[CO_2], is predicted to rise from the present value of 350 to 460 ppm, a revision to a somewhat lower value than previously suggested. Not withstanding the inherent scientific complexity of the problem, assessment of the potential impact of those changes on the yield and structure of the Australian wheat industry is made even more difficult by the range of environments it encompasses and by their inherent variability.

PRODUCTION OF WHEAT IN AUSTRALIA

Wheat is grown widely through southern Australia (Fig. 1). The area involved is large because each year's crop is mostly grown in rotation with legume-based pasture and more recently with other crops, especially grain legumes and canola, but also other cereals, oat, barley and triticale. Year-long fallows are also included in rotations in many areas, further increasing the area involved in wheat production. In all, the area involved is probably around 60 Mha.

The area sown annually to wheat over the past 40 y is depicted in Figure 2a. There was a relatively continuous increase from around 4 Mha in the mid 50s to around 12 Mha in the mid 80s. The break to that pattern in the early 70s occurred when production quotas were imposed by the Australian Wheat Board. The second, the decline during the last decade has occurred as growers have turned to other activities in response to the low prices that have resulted from oversupply on the world market. In the past, growers adjusted wheat production mostly by changing the proportion of land allocated to wheat and pasture for sheep. However, during recent years that method of adjustment has become unprofitable because of low prices for wool. Under these conditions, other crops have become important components of rotations of Australian wheat farms. For example in Western Australia on acid soils, narrow-leaf lupin increased in area from 1000 to 1 Mha in the ten years from 1980 to 1990. In

Victoria, where soils and climate are more suited to field pea, the area of that crop has increased from negligible amounts to 0.2 Mha during the same period.

In Australia, productivity of wheat is low and variable because the crop is grown is drought-prone regions without irrigation. Fig. 1 shows that it is concentrated in zones where annual rainfall is between 300 and 700 mm. The average national yield is highly variable as seen in Fig. 2b. Over the 40-y period since 1950, there has been a consistent, slow increase in yield (c 10 kg/ha/y), but the dominant impression is one of variability. Comparison with yield statistics for other major wheat exporting countries identifies Australia as the country with the most variable yield (Rimmington and Connor 1991). While this characteristic makes marketing difficult, that large national variability obscures even greater variability within the component regions of the nation and more still on individual farms.

The variability that is seen in yields exists despite the best attempts of farmers to minimise it. Under the prevailing climatic and economic conditions, many cultural practices that farmers have employed in the past have been directed towards minimising variability. Fallowing, for example, has its major effect on stabilising the yield of fewer crops than on maximising the total production possible in an area. In the same way, farmers are cautious with nitrogen and most of the crop is grown without fertiliser, relying on residual nitrogen accumulated previously by legumes in the rotation (Loomis and Connor 1992). The problem, there, is that while there are opportunities to increase yield in some places and some seasons with nitrogen fertiliser, it is also possible to obtain no response or even to induce a yield depression with a relatively expensive input. Scientists are just beginning to understand how to sort out some of those issues under present climatic conditions using crop simulation models. The approach, if successful, will continue to be applicable under changed climatic conditions provided it is possible to define their characteristics.

National wheat production carries much but not all of the variability that was seen in yield (Fig. 2c). This is mostly because of the variability of yield but also because of the way adjustments to crop area are made. When crop area is reduced in response to economic factors, the most marginal areas are taken from production when the prospect of good prices encourages expansion of production, that marginal land is returned to production. Thus, during the time of steadily increasing crop area in the

70s (Fig. 2c), there was considerable variation in production. The peak production of 22 Mt in 1983/4 was achieved at 1.70 t/ha from 12.9 Mha.

CLIMATE OF THE WHEAT ZONE

The wide geographic range (Fig. 1) means that wheat is grown in locations with various seasonal combinations and annual totals of rainfall, temperature, daylength, and solar radiation. In practice, what happens in Australia and other places also, is that wheat is grown at locations and during the period of the year that has the temperature regime most suited to its thermal requirements and tolerances. This means spring crops are grown in continental climates and winter crops in temperate climates. Within the tropical latitudes, suitable thermal regimes are found only at high altitudes. As a temperate C3 species, the temperature optimum for growth of field crops is broad in the range 15 to 25 C. Growth is reduced at temperatures outside this range but extremes (<-5 or >35 C) are detrimental only at critical times. The most sensitive stages are those around anthesis. Given an appropriate thermal regime, the challenge is then to select or breed cultivars with developmental responses appropriate to particular seasonal patterns of daylength. That has proven to be a soluble problem because development is controlled by few genes which are susceptible to manipulation and in the extreme it has been possible to select cultivars that are photoperiodically insensitive. That strategy has been employed by CIMMYT in its search for cultivars of wide geographic adaptation.

These points are stressed here because the wide range of germplasm that is already in commercial use or in breeders nurseries contains genotypes that are widely adapted to thermal and photoperiodic regimes. There exists a genetic bank from which to select or to develop cultivars for the warmer thermal regimes resulting from climatic change, in all locations except at the hottest margins of wheat production areas. This is certainly the case for rainfed wheat production in Australia. There, apart from quantifying the beneficial effect of elevated [CO_2], the issue of climatic change reduces to the impact of some new non-optimal temperature regime on the growth and yield of wheat bearing in mind that higher temperatures will increase evaporative demand an hence, without additional rainfall, increase the extent and pattern of water stress that crops experience. Rainfall, then, remains the central climatic parameter.

There is wide variation in the distribution of rainfall across the Australian wheat zone. Some contrasts are shown in Fig. 3 as a transect of sites from south east (Minnipa, SA), to central east (Wagga Wagga, NSW) to north east (Miles, Qld). Rainfall has a winter-spring incidence in the south (and also in western Australia, not shown here), is evenly distributed throughout the year in the central part, while in the north there is a marked summer incidence. The distribution of rainfall relative to the thermal regime controls the growing season and the cultural practices employed. Fallowing is the only practice available to increase the water supply to rainfed crops in water-short regions. It is, however, an inefficient process with maximum efficiencies of storage of concurrent rainfall generally less than 25 % (Loomis and Connor 1992). There is much loss from the soil surface, the amount depending upon the extent and frequency of rains but unless the soil has high water-holding capacity, there is additional loss by drainage to depth below the root zone.

There are two extremes to the process of fallowing. In areas of low rainfall. fallows are maintained for the year prior to sowing in order to conserve sufficient water for economically viable crop production. In areas of significant summer rainfall, a short fallow following harvest of a previous crop may be adequate. As a general rule, clayey soils are favoured and sandy soils are unsuitable for water conservation in all rainfall regimes.

Given the distribution of rainfall in north-east wheat zone (e.g. Fig. 3c) summer fallows on clay soils are essential to success while in the central part of the zone, where rainfall is evenly distributed throughout the year (Fig. 3b) summer fallows supplement crops that receive little growing season rainfall. In the south (Fig. 3a) and especially in the west, rainfall is winter dominant. There, summer fallows protect water stored in the soil profile during the previous winter and spring, but long fallows are required to ensure adequate water storage in the regions of lowest rainfall.

RAINFALL VARIABILITY AND ENSO

ENSO is a major climatic phenomenon known to effect the rainfall of eastern Australia. It's condition, known as the Southern Oscillation Index (SOI), is determined from differences in atmospheric pressure between Tahiti in the mid Pacific and Darwin in north-east Australia. The pressure pattern is responsible for macro-scale effects on prevailing wind directions in the Pacific. High pressures in the mid Pacific bring easterly winds, moisture and above-average rains to eastern Australia. Under the opposing conditions, winds are off-shore and rainfall is below average. An important feature of the system is the tendency for slow but erratic build up of dry conditions and then rapid reversal. The consequence is the large variability of rainfall in the region. The poem that describes Australia as ".. a land of droughts and flooding rains" now has scientific explanation.

The influence of ENSO on rainfall patterns is sufficiently strong that national wheat yields are correlated with SOI. Figure 4 presents such correlations between monthly values of SOI and Australian wheat yield over the past 40 y (Nicholls and Rimmington 1993). The correlations show the strongly biennial nature of the oscillation. In the current crop year yields are positively related to SOI (strongly positive numbers indicate a likely wet year) but are negatively correlated with SOI of the previous year (strongly negative numbers indicate a dry year that is likely to be followed by a wetter, current year). Considerable variability remains but that part explained by SOI is now used to make long-term rainfall forecasts that can be incorporated in Decision Support Systems to assist tactical crop management (Russell 1990) particularly those concerning nitrogen management, plans for harvest and sale of grain, and provision of fodder for stock.

CLIMATIC CHANGE AND AUSTRALIAN WHEAT PRODUCTION

From the previous discussion it is evident that increased [CO_2] and temperature and a changed pattern of seasonal rainfall would have interacting effects on the growth and yield of wheat crops. Photosynthesis and therefore growth should increase in response to greater [CO_2]. Higher temperature would have interacting effects on crop water demand. On the one hand, it would increase the rate of water use, especially at the end of the season when temperature is highest. On the other hand it would hasten development, shorten the crop cycle and reduce total water demand. During winter, higher temperature would promote growth but the grain-filling period would become a focus of interest because the crop is then especially susceptible to heat and water stress.

Simulation models are well suited to the analysis of the effects of climatic change on crop production. In this paper we present preliminary analyses of the effect of increased [CO2] and higher temperature on the performance of wheat at two locations in southern Australia. The analyses were made with a simulation model of the wheat crop designed to assess the interacting effects of [CO_2], temperature, solar radiation, rainfall, and evaporative demand on crop development, growth and yield (Handoko 1992, Wang et al 1992). In an earlier stage of development, the model was used to assess the effects of climatic change on potential wheat yield in Victoria (Wang et al 1992) and more generally (Leuning et al. 1992). Since then the grain-growth submodel has been completed so that the model now appropriately predicts actual grain yield under water-limited conditions. Because it does not account for hazards other than environmental ones that afflict wheat crops in the field, e.g. weeds, pests, inadequate nutrients etc., the predictions are appropriately interpreted to approximate the yields of the best crops observed in the field.

The study concerns the performance of three cultivars in response to climatic change at two locations in the southern Australian wheatbelt. The sites were selected because they represent important climatic zones where wheat is grown and because complete environmental data is available for them. The cultivars were chosen because they have distinct and quantitatively defined patterns of phenological development Loss et al. 1990, Perry et al. 1987). Details of sites and cultivars are presented in Tables 1 and 2, respectively.

The study has two aspects. The first is the analysis of yield response of the three cultivars to temperature and [CO_2] covering the range of predicted climatic change. The second, is an exploration of the potential value of manipulating developmental patterns as an aid to the design of cultivars more suited to present or modified climatic conditions. A weather generator was used to form annual sequences of temperature appropriate to the present climatic regime for each location. The temperature-change scenarios were constructed by simply adding each consecutive temperature increase to the random sequences. Apart from that, historical data sequences (47 y) provided radiation, rainfall and windrun for each location.

RESPONSE OF THREE EXISTING CULTIVARS TO TEMPERATURE AND [CO2]

For this study, crops were grown at 5 day intervals during the normal period of sowing in each year. The results are summarised as mean yield and standard deviation in Fig. 5 for Mildura and in Fig. 6 for Wagga. Yields are smaller at Mildura than at Wagga, reflecting the lower rainfall there. Mean yields for the present climatic regime range from 0.63 (sd 0.14) t/ha for the short-season cultivar Sunset at Mildura to 4.01 (sd 1.30) t/ha for the long-season cultivar at Wagga. At both sites, greatest yield is achieved using the longest-season cultivar. Variability is large in all combinations, increasing characteristically with yield. In this rainfall environment, the large yield possible with long-season cultivars is achieved with the risk of high variability.

The responses to increasing temperature and [CO_2] present a consistent pattern. Yield is predicted to increase with a rise in [CO_2] from 350 to 460 ppm and to decrease as temperature rises by 3 C. The increases and decreases are roughly in proportion to yield under the present climate. Over all cultivars, mean response to [CO_2] under the present temperature regime is +23 % at both sites, while the combination of 460 ppm and +3 C is predicted to reduce yield relative to present conditions by 37 % at Mildura and 51 % at Wagga. No simulations were performed at intermediate [CO_2], but the marked response to small temperature increase shows the effect of climatic change would be relatively greater in the early stages than later.

THEORETICAL ANALYSIS OF CULTIVAR CHARACTERISTICS

This aspect of the study compared the effect of changing the developmental pattern of each cultivar while maintaining the same cycle length. Simulations were made for crops sown at the optimum time (day 135) for 47 y. The thermal time from sowing to stem extension was varied widely in steps of 40 d deg from that shown in Table 2 while maintaining the existing duration of the overlapping phenophase of sowing to anthesis. The other phenophases, sowing to emergence and anthesis to maturity were held constant to the values shown in Table 2. The effect is to change the balance in duration of growth before and after stem extension.

In the model the main effect of this modfication is to affect the partition of biomass between leaf growth, stem growth and the growth of the developing inflorescence. Spikes begin growth at stem extension and continue until anthesis. The number of grain is assumed to be proportional to spike dry weight at anthesis (Fischer 1980). Increase in the duration of the phenophase stem extension to anthesis increases spike growth and hence grain number. On the other hand, the rate of spike growth depends upon crop photosynthetic rate which is related to canopy leaf area index (LAI). Increased duration from sowing to extension allows the development of larger LAI which will intercept more radiation and hence increase spike growth after stem extension. The optimal balance of duration of growth periods before and after stem extension is thus complex and will vary from year to year depending upon weather conditions.

Results of the simulations are shown for cv Bencubbin at Mildura. They suggest that a slight relative increase in growth duration before anthesis would provide the optimal pattern for maximum yield under present climatic conditions. Any substantial increase, however, would result in a significant yield loss. What is of more interest here is that the simulations suggest that similar yield distributions could be achieved at higher temperatures by increases in the relative duration of the phenophase emergence to stem extension. Greater yield than at present could be obtained by such a breeding strategy under the anticipated combination of high temperature and the causal increase in [CO_2]. Wang et al. (1992) have previously suggested that successful adjustments to modified climates might be accomplished with adapted cultivars. This study shows one way in which it may be achieved.

DISCUSSION

The small and variable yield of Australian rainfed, wheat crops reflects the low and variable rainfall over the wheat growing areas. A recent major scientific advance has been the elucidation of the role that ENSO plays in determining rainfall in eastern Australia. The relationship can be seen in the correlations that exist between SOI and national and regional crop yield. Analyses of historical patterns of SOI have improved seasonal rainfall forecasts that will assist growers and marketing authorities to reduce the difficulties associated with high variability of rainfall.

The climate change scenario currently applied to the Australian wheat zone combines a temperature increase of up to 3 C with a rise in [CO_2] from 350 to 460 ppm by the year 2030. It is also thought that during this period there will be compensating changes in rainfall, viz. less winter rainfall (-10 %) and more summer rainfall (+20 %). Assessment of the effect of these changes must be made within the context of the variability and wide range of temperature and rainfall patterns that exist within the wheat zone. Conditions of temperature and rainfall are presently sub-optimal in all locations, the effect of climatic change would be to produce a different set of sub-optimal conditions to change the balance of climatic advantage and disadvantage to the growth and yield of wheat. Simulation models offer the best opportunity to assess the impact of these changes and it is shown here that the advantage to plant growth that would result from CO_2 fertilisation (+23%) will be more than offset by yield reduction resulting from the effect of associated higher temperatures. Higher temperatures have their major effect by shortening the growth cycle of current cultivars and increasing the evaporative demand and hence water stress, particularly during grain filling. The estimates made here are for yield reductions of 37 to 51 %

for the combined effects of increasing temperature and [CO_2] depending upon present rainfall. The smallest reductions are predicted to occur at locations of low rainfall and consequent yield.

The model was also used to assess the possibility of combating the effect of climatic change by breeding cultivars better suited to changed climatic conditions. This has been a theme in previous studies of climatic change and crop production including the Australian wheat zone (Wang et al. 1992). In the study undertaken here, the focus was on the effect of changing the phenological pattern of an existing cultivar to adjust the balance of growth during the vegetative period before and after anthesis. The analysis shows significant responses, suggesting this technique as a possible way to maintain yield at higher temperature and [CO_2].

The model used here incorporates the direct effect of CO_2 on crop photosynthesis. This is not a consistent feature of other crop simulation models that have been applied to the assessment of the effect of climatic change on crop production. However, the model does have limitations because it does not include other physiological responses to CO_2, for example, well established effects on partitioning of assimilates to and within component organs. While simulation models offer the most realistic method the assess the impact of climatic change, their continuing improvement is required to increase their physiological content and applicability to the task.

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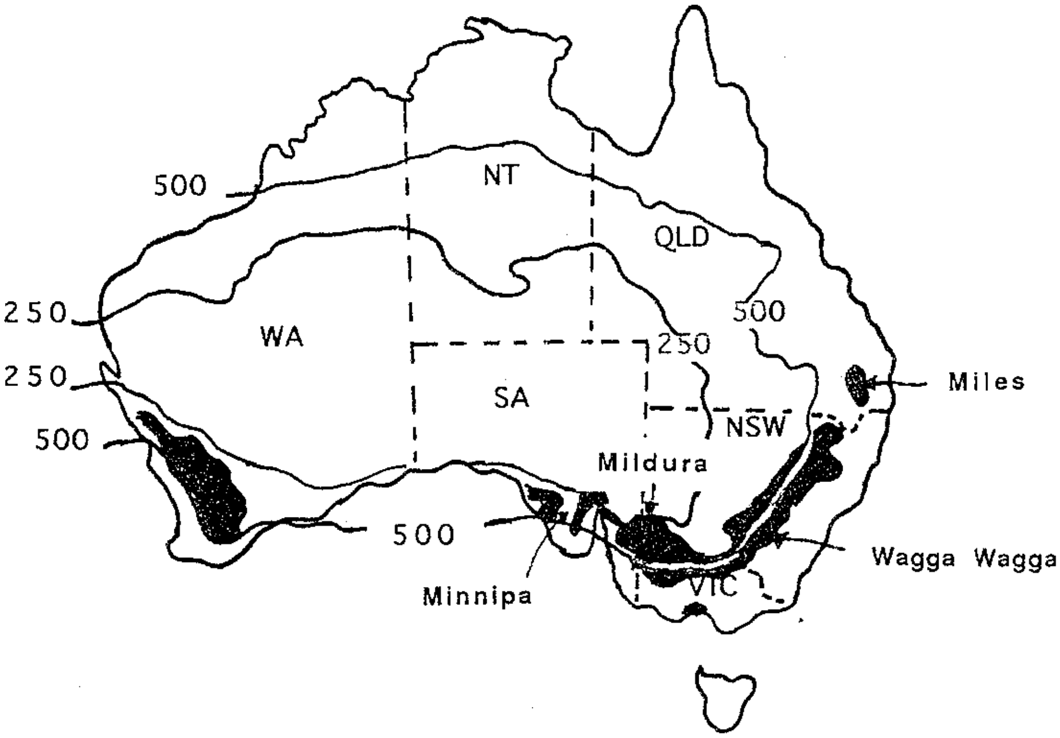


Figure 1. Distribution of wheat production in Australia in relation to annual rainfall. Also shown are the locations of sites referred to in the text.

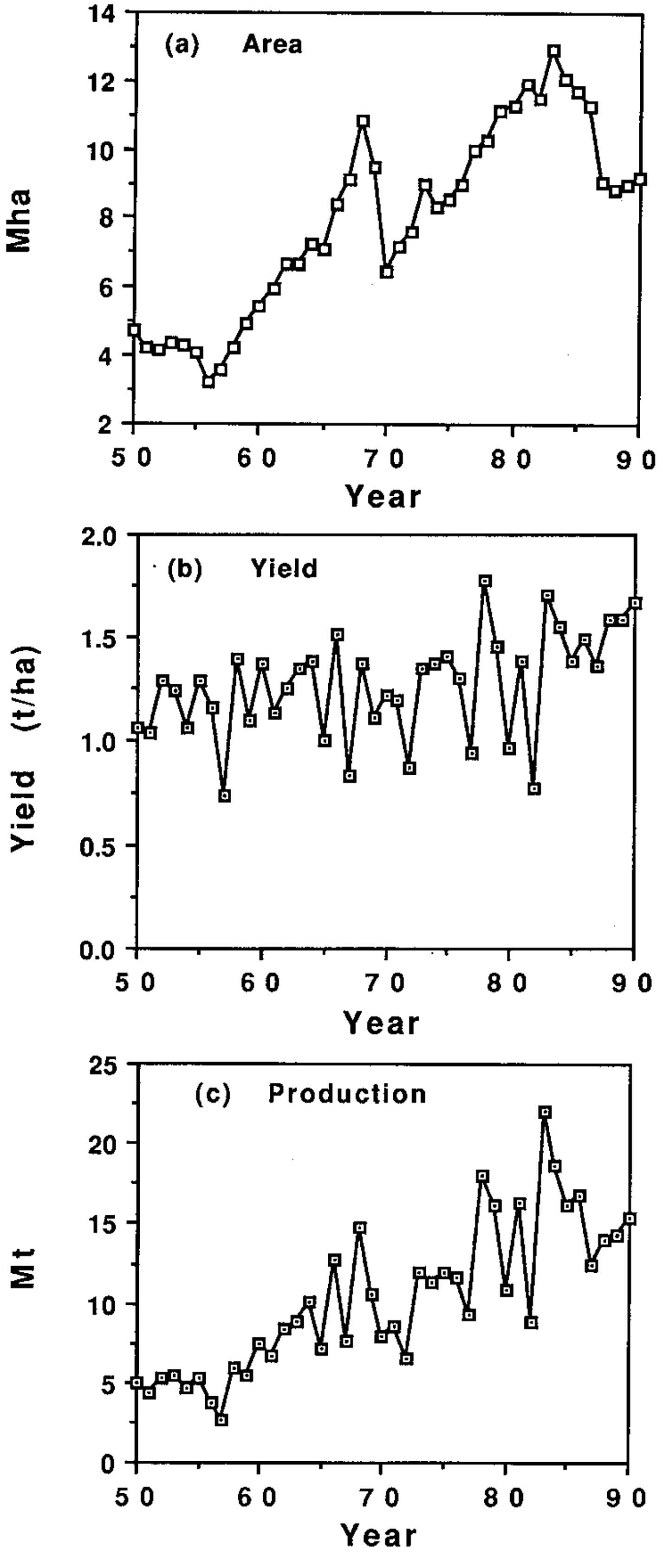


Figure 2. Annual wheat production statistics for Australia for the 40-year period 1950 to 1990. (a) area (Mha), (b) yield (t ha^{-1}), and (c) national production (Mt).

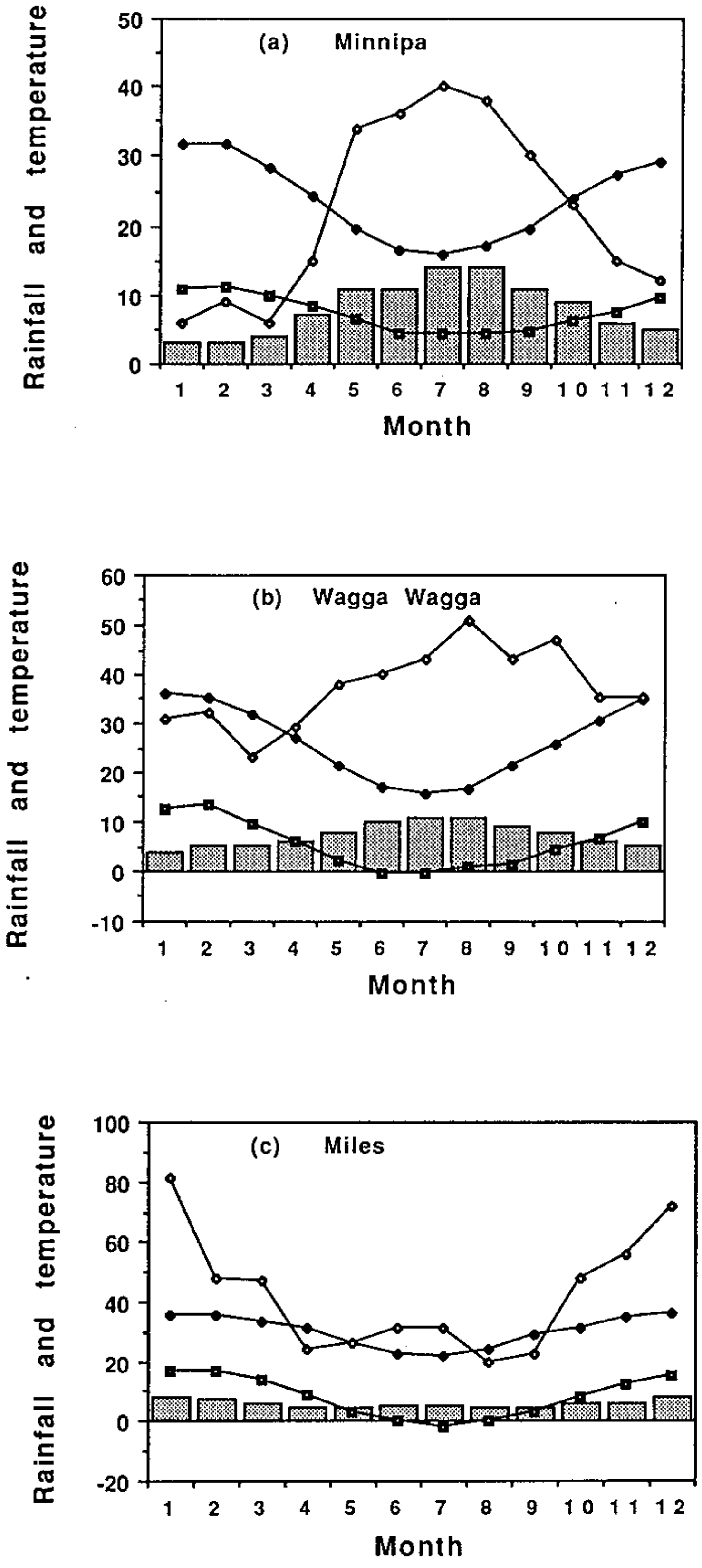


Figure 3. Monthly distributions of rainfall (mm) and temperature (^{0}C) at selected sites in the wheat zone of eastern Australia. (a) Minnipa, South Australia, (b) Wagga Wagga, New South Wales, and (c) Miles, Queensland.

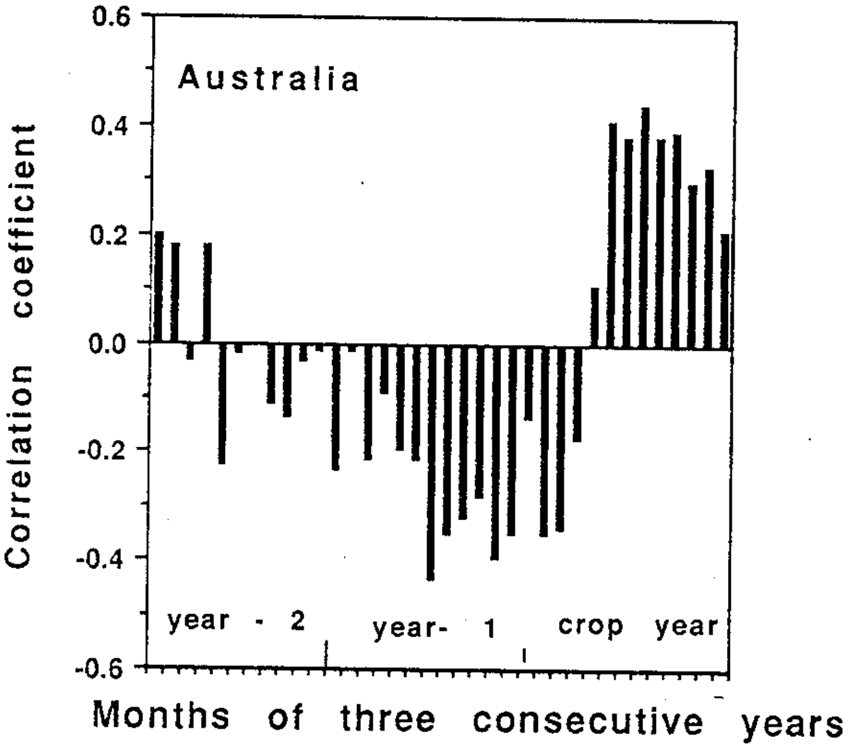
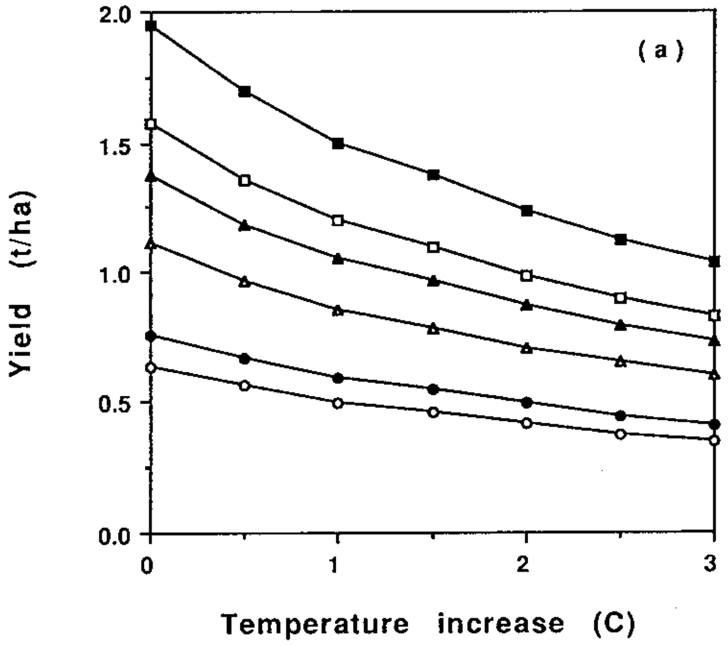


Figure 4. Correlation coefficients for detrended wheat yield and monthly values of the southern oscillation index over the period 1948-1988 for Australia. Year is the crop year, year-1 is the previous year, and year-2 is the year before that.



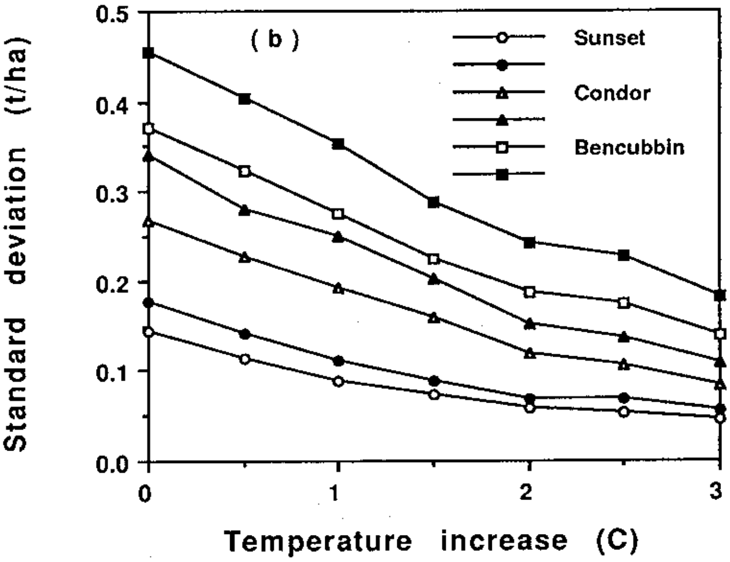


Figure 5. Simulated wheat yields of three cultivars, Sunset, Condor and Bencubbin at Mildura, under present environmental conditions (350 ppm CO_2, open symbols) and the separate effects of increasing [CO_2] to 460 ppm (closed symbols) and mean temperature by 1, 2 and 3 C. (a) mean yield and (b) standard deviation.

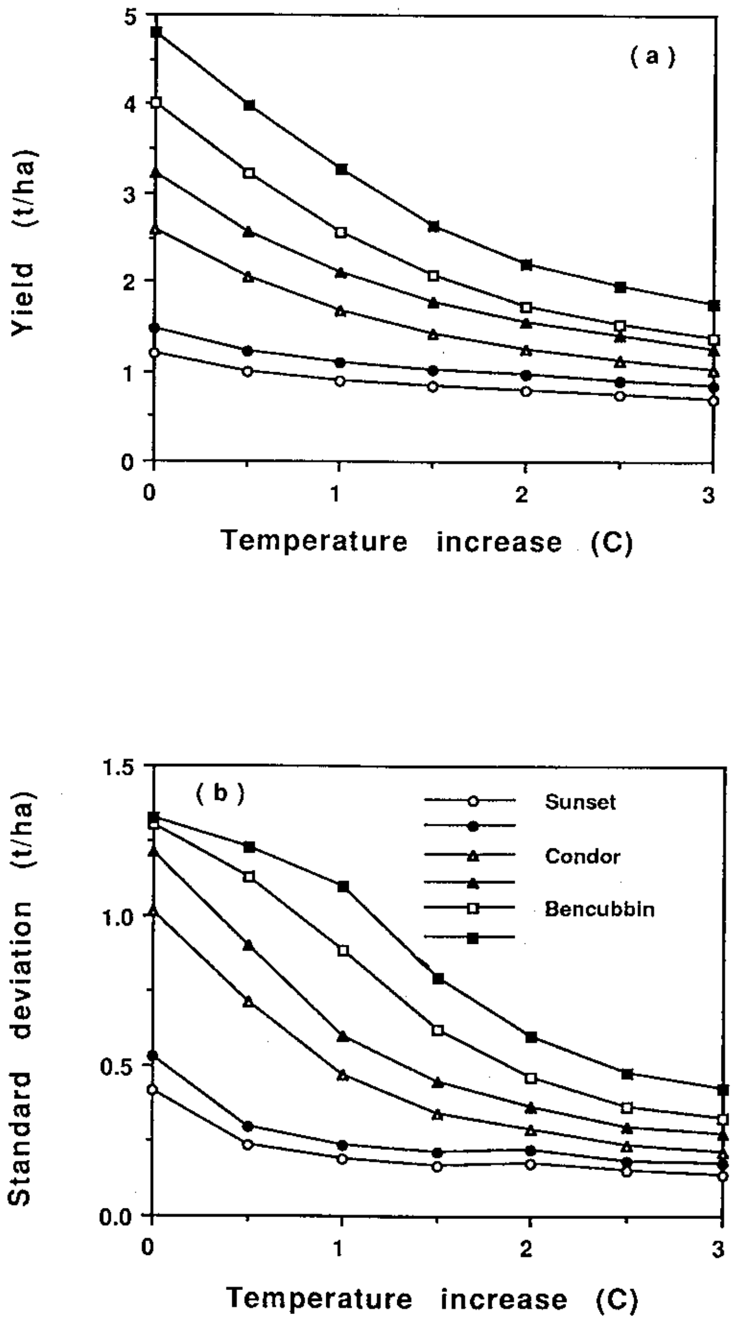


Figure 6. Simulated wheat yields of three cultivars, Sunset, Condor and Bencubbin at Wagga Wagga, under present environmental conditions (350 ppm CO_2, open symbols) and the separate effects of increasing [CO_2] to 460 ppm (closed symbols) and mean temperature by 1, 2 and 3 C. (a) mean yield and (b) standard deviation.

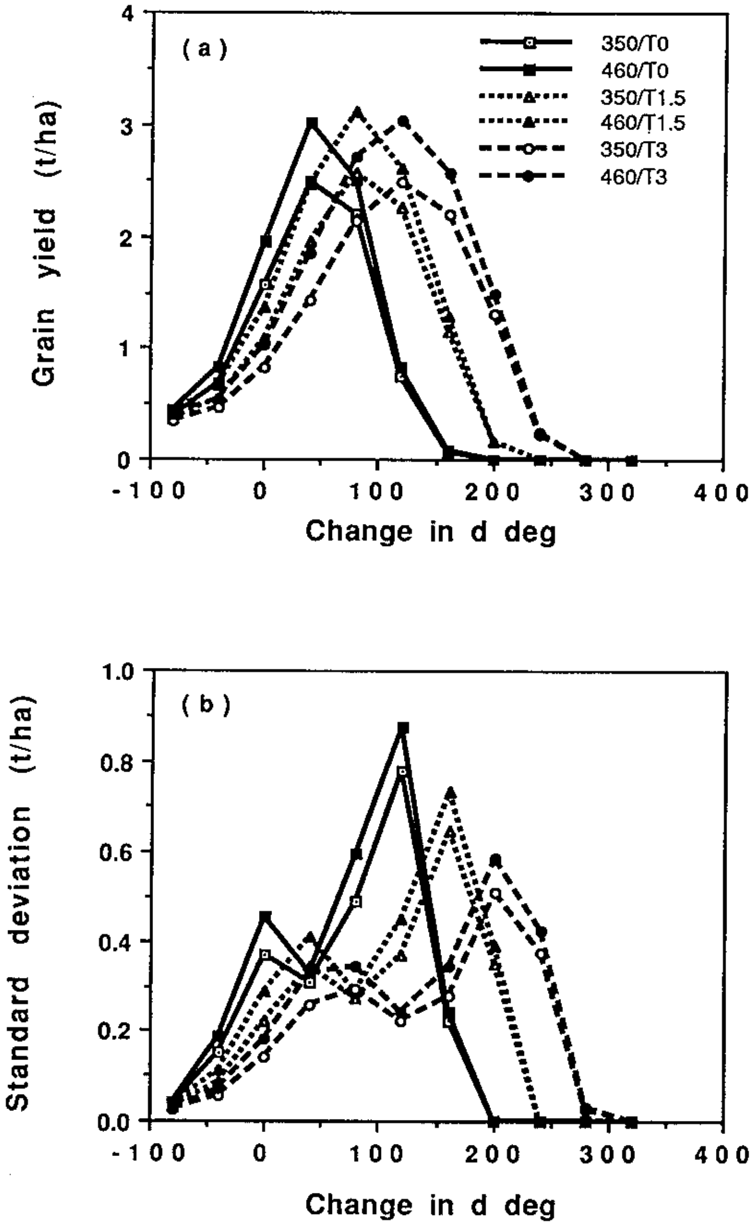


Figure 7. A simulation study of the effect of manipulating the phenological development of cv Bencubbin by varying the duration from sowing to stem extension from the cv value of 360 d deg (> 4 C) while maintaining the same photothermal duration for the total period from sowing to anthesis of 9060 d deg h (>2 C, > 6 h). Simulated yields are shown for present environmental conditions at Mildura and the effect of increasing [CO_2] to 460 ppm and mean temperature by 1, 2 and 3 C. (a) mean yield and (b) standard deviation.

Table 1. Long-term climatic data for two study sites.

	Location	
	Mildura	Wagga
Latitude (^{0}S)	35	35
Altitude (m)	50	219
Annual rainfall (mm)	333	539
Raindays	71	88
Mean daily max. temperature	23.7	21.8
Mean daily min. temperature	9.6	9.6
Mean rel. humidity % (9am)	65	68
Mean re. humidity % (3pm)	39	-
Evaporation (mm)	1600	1500

Table 2. Phenological characteristics of three cultivars used in the simulations.

		Cultivar	
Phenophase	Sunset	Condor	Bencubbin
Thermal time sowing to emergence (d deg > 2.6 C)	78	78	78
Thermal time (d deg, > 4 C) sowing to stem extension	280	320	360
Photothermal time (d deg h > 2 C > 6 h) sowing to anthesis	6100	7400	9060
Thermal time (d deg > 8 C) anthesis to maturity	416	416	416