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EFFECTS OF CLIMATIC VARIABILITY AND POSSIBLE CLIMATIC CHANGE ON RELIABILITY OF WHEAT CROPPING — A MODELLING APPROACH

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ABSTRACT

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Wheat cropping in the northern sector of the Australian wheat belt has been expanding into a region with a more marginal moisture regime and a more variable climate than in the established cropping regions. To provide a sound basis for land use assessment, the likely reliability of cropping in this region was examined. Reliability included the likelihood of planting a wheat crop in any year and the likely yield of planted crops. Simulation studies, using an appropriate model of the cropping system and long-term rainfall records (92-year period), were used to derive yield probability distributions for sites throughout the region. The main features of the cropping system model developed are outlined. The yield probability distributions and associated economic analyses indicated that expansion of wheat cropping in this region was likely. Trends in simulated yield sequences were compared with analyses of factors associated with recent climatic change. Similarities of patterns suggested an association of rainfall and yield trends with climate forcing factors. Implications of this association are discussed. A better understanding of the action of the climate forcing factors is required before possible climatic change can be included in determining reliability of cropping.

INTRODUCTION

In recent years dryland wheat cropping has expanded in the northern sector of the Australian wheat belt (Fig. 1). This expansion has occurred westward

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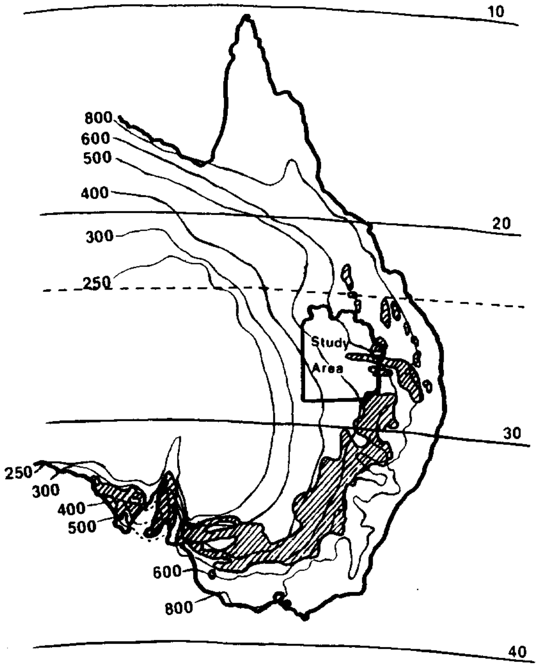

Fig. 1. Main wheat-growing areas (hatched) in mainland eastern Australia and relevant isohyets of mean annual rainfall (mm). The study area of the Maranoa and Warrego region of Queensland is outlined. (Adapted from Nix, 1975)

into regions with higher evaporative demand and lower, more variable rainfall than that in the traditional wheat-growing areas immediately to the east. Agricultural land use in these western regions has been dominated historically by grazing. The particular region of interest is the Maranoa and Warrego region of Queensland (Fig. 2). Summaries of the climatic features of this region and their general impact on agriculture have been reported by Weston et al. (1975) and Lloyd and Hamilton (1984).

Nix (1975) presented a comprehensive, agroclimatic analysis of wheat-growing in Australia. He found large potential for expansion in the northern sector of the Australian wheat belt. In this sector seasonal rainfall must be supplemented by stored soil water for successful production. However, Nix's analysis indicated that short (four to six month) summer fallows between successive wheat crops are usually sufficient to recharge soil profiles. He noted that the major limitations in the northern sector are the availability of soils with favourable water-retention characteristics, the erodibility of bare-fallowed soil under high intensity summer rainfall, the relatively high variability of winter rainfall and the associated greater uncertainty of receiving adequate sowing rains. All of these factors are relevant to the expansion occurring in the Maranoa and Warrego region.

Details of the soils of the region and their suitability for cropping have been

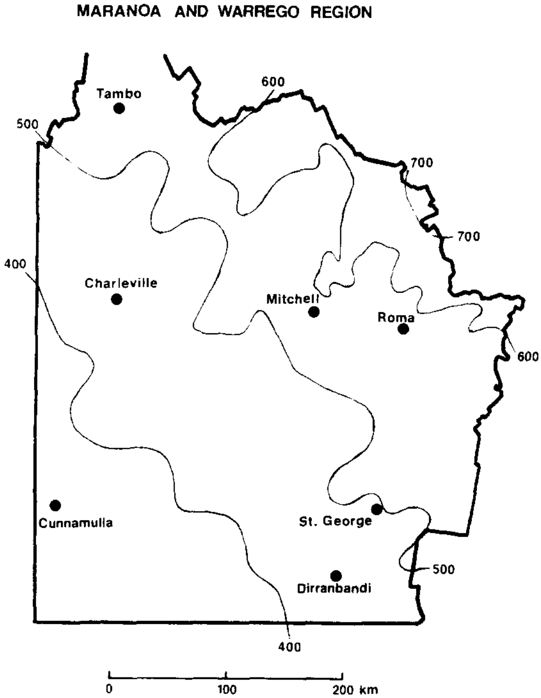

Fig. 2. Maranoa and Warrego region of Queensland showing principal locations and isohyets of mean annual rainfall (mm).

reported by Vandersee and Slater (1984). There are large areas of moderately deep, cracking clay soils with high water-retention capacity. With the use of suitable soil erosion control practices, these soils are considered physically suitable for cropping. The westward expansion of cropping on these soils is associated with a more marginal moisture regime. Possible causes of this recent expansion are: (i) economies of scale associated with technological advance have reduced the yield level required for profitable cropping, and (ii) a series of favourable years have spurred speculative development. In relation to (ii), analyses of long-term rainfall records (Russell, 1981) indicated that for this region a series of years with generally above average summer rainfall commenced about 1945. This may be associated with possible recent climatic change which has been linked to a cyclic variation of solar luminosity (Gilliland, 1982). High summer rainfall is advantageous to the wheat crop in this region via recharge of the soil profile during the summer fallow. The decade of the 1970's was particularly favourable and wheat yield levels in 1978 were the highest on record. It is not known whether the areas recently converted from pasture to wheat cropping can sustain this form of land use in the long-term given the low average and highly variable rainfall of the region and possible consequences of climatic change.

The objective of this study was to quantify the reliability of wheat cropping in this region and thus provide a basis for land-use assessments. Reliability includes the likelihood of planting a wheat crop in any year and the likely yield of planted crops. In the Maranoa and Warrego region, water limitation is the major factor controlling production. Hence, the amount and distribution of rainfall and its variability from year to year have a large influence on the reliability of cropping. Simulation studies using a suitable model of the cropping system in conjunction with long-term rainfall records provide a means for quantifying the reliability of cropping. Such a modelling approach was adopted in this study.

METHODS

Overview

A dynamic simulation model of a continuous wheat-cropping system was developed. Simulation studies were undertaken for a number of sites throughout the Maranoa and Warrego region. Long-term records (90 years) of daily rainfall and long-term average temperature and evaporative demand data were inputs to the model. The use of current technology and wheat varieties was assumed. Thus, long-term sequences of simulated yields, dependent only on the location and the rainfall variability, were derived. The simulated yield sequences were used to examine the reliability of cropping throughout the region by constructing yield probability distributions. The yield sequences were compared with long-term patterns and factors possibly associated with climatic change. These comparisons were used to consider the validity of using yield probability distributions derived in this manner for future decisions. The comparisons also provided a basis for discussing possible consequences of climatic change.

The dynamic cropping-system model had a daily time step and consisted of a number of sub-models. A soil water balance was maintained through the summer fallow. A planting criterion was developed from examination of local farm records and when this criterion was met the simulated crop was planted. Crop growth and development sub-models, interacting with soil water and nitrogen sub-models, simulated the cropping phase. The crop yield sub-model determined the yield for the crop for that particular year. At physiological maturity, the system was returned to fallow until the next potential crop in the following year.

It is not intended to give a full, detailed description of the model. However, the main features of each of the sub-models will be described.

Crop yield sub-model

Yield of wheat has been closely linked to crop growth potential over a short period around anthesis by Woodruff and Tonks (1983). They derived a yield index (GYI), such that

$$GYI = (T/E_0)(1/T_m)$$

where T = transpiration (mm), E_0 = class A pan evaporation (mm), and T_m = mean daily temperature (°C), all for the 20-day period centred on the day of anthesis. This index integrates the effects of growth duration, anthesis date, and environment. It accounted for a large proportion of the grain yield variation for a large number of experiments over a wide range of environments in the northern sector of the Australian wheat belt. One of the equations for grain yield, presented by Woodruff and Tonks (1983), based on this index, was used in this study for yield prediction. The equation chosen was the most relevant for the genotype grouping most commonly used in the region of interest. It was

$$Y = \text{MIN}\ (148,\ 25 + 0.22\, TDWA) + 2833\, GYI + 46291\, GYI^2$$

where Y = grain yield (g m^{-2}), MIN = minimum value of the two expressions and $TDWA$ = total dry weight at anthesis (g m^{-2}). The term incorporating $TDWA$ was included to improve precision for low-yielding crops (Woodruff, pers. commun., 1984).

$TDWA$ and the components of GYI were calculated in the crop growth and soil water sub-models and the timing of anthesis was determined in the crop development sub-model. Once these estimates of the relevant components were available, the yield prediction was determined in the crop yield sub-model.

Crop growth sub-model

Given the planting date and starting condition in any year, this sub-model was required to generate $TDWA$ and the relevant components of GYI for use in the crop yield sub-model. Hence, estimates of crop growth and leaf area development were needed to derive $TDWA$ and T. Crop models, suitable for adaptation to this task, but with varying degrees of complexity have been reported (Fitzpatrick and Nix, 1969; van Keulen, 1975; Berndt and White, 1976; Morgan, 1976; Hammer and Goyne, 1982; O'Leary et al., 1985). The level of complexity required is associated with the objective of the study (Hammer, 1981) and for studies of this nature a model intermediate in complexity between a fully empirical and a fully mechanistic model is required. The approach adopted was similar to that of Hammer and Goyne (1982) and O'Leary et al. (1985) although it was developed independently of the latter.

Crop growth rate (CGR, $\text{g m}^{-2}\ \text{day}^{-1}$) was estimated as the product of the transpiration amount (T, mm day^{-1}) and the transpiration efficiency (TE, $\text{g m}^{-2}\ \text{mm}^{-1}$). This procedure was adopted as it was robust (Tanner and Sinclair, 1983) and appropriate to water-limited environments. TE is dependent on evaporative demand and the empirical relationship reported by Fischer (1979) was used to account for this dependence (Fig. 3).

A root:shoot ratio and leaf area ratio, both dependent on stage of develop-

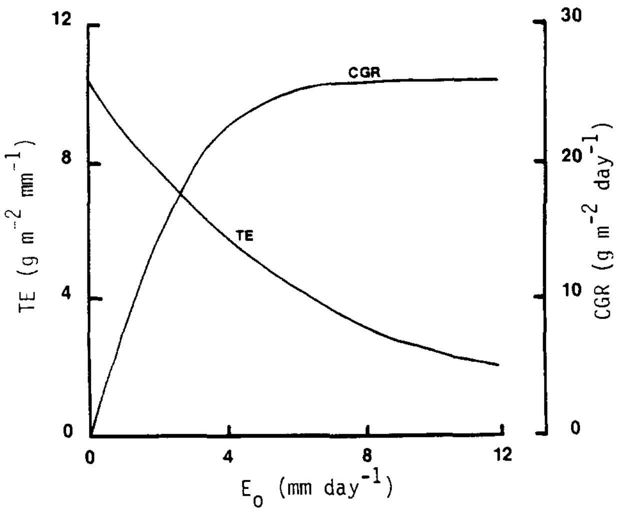

Fig. 3. Form of main relationship used in crop growth sub-model. The curve for transpiration efficiency (*TE*) is taken from Fischer (1979). The curve shown for crop growth rate (*CGR*) is for the case where canopy cover is complete and no water limitation exists, i.e. transpiration (*T*) equals class A pan evaporation (E_0) so $CGR = T^*TE = E_0{}^*TE$.

ment, were used to convert *CGR* to above ground growth in mass and area. Hence, total dry weight (*TDW*) and leaf area index (*LAI*) were determined by accumulation. Crop development was maintained in the appropriate sub-model so that at anthesis the variable *TDWA*, required in the yield sub-model, was defined. The effects of water and/or nitrogen limitation on *LAI* were incorporated using dimensionless stress indices (*WSI* and *NSI*) derived from the soil

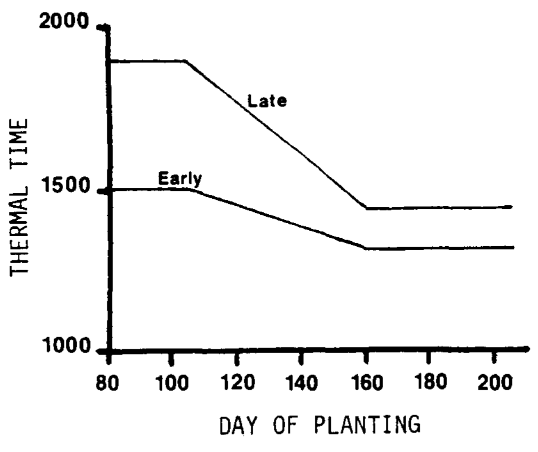

Fig. 4. Thermal time (degree-days) between emergence and anthesis for a range of planting times for early- and late-maturing wheat genotypes. (degree-days = Σ ((max + min)/2 − base); base = 0°C)

water and nitrogen sub-models, respectively. *WSI* and *NSI* were used to modify rates of leaf area production and loss. *LAI* was used to calculate the variable T required in the yield sub-model. This calculation was performed in the soil water sub-model.

Crop development sub-model

Data were available (Woodruff, 1983) for the construction of generalized rate of crop development models similar to those reported by Angus et al (1981). However, as the geographic spread of sites being considered was within a limited latitude range, a simpler approach using results from local field trials (unpublished data, QWRI) was devised. From these data, the dependence of thermal time from emergence to anthesis, on date of planting and maturity grouping, was determined (Fig. 4). Time from planting to emergence was predicted using the thermal response reported by Angus et al. (1980). Hence, for any given date of planting, the date of anthesis could be predicted and the values of the variables E_0 and T_m, required in the yield sub-model, could be determined.

Timing of physiological maturity was predicted by accumulating 650 degree-days (base temperature 0°C) thermal time after anthesis. Harvest was simulated once five dry days had occurred after physiological maturity.

Soil water sub-model

This sub-model was used throughout both the fallow and crop phases. The soil was divided into three depth layers: 0–10 cm, 10–60 cm, and 60 + cm. The soil type assumed at all sites had a depth of 72 cm and a plant available water capacity of 137 mm. These characteristics were determined from a field site near Roma (Fig. 2). In this sub-model the moisture content of each layer was maintained by removal of predicted soil evaporation and transpiration, and addition of infiltrated rainfall.

Potential daily evapotranspiration was taken to be the class A pan evaporation (E_0, mm day^{-1}). Analyses by Fitzpatrick (1968) indicated little advective effect during the cropping period throughout the study region. Hence, E_0 was a reliable estimate of potential evapotranspiration. E_0 was partitioned to potential soil evaporation (SE_p) and potential transpiration (T_p) using energy interception functions dependent on *LAI* (*GCOV* and *SCOV*, Fig. 5). Hence,

$$SE_p = E_0 (1 - SCOV)$$

and

$$T_p = E_0 \, GCOV$$

The differences between *SCOV* and *GCOV* account for the effects of soil surface wetness in a manner similar to that reported by Ritchie (1983).

Whether or not these potential amounts could be achieved depended on the amount of soil water and its distribution through the profile. Daily actual soil evaporation (SE) was predicted using the method of Rickert and McKeon (1982) which distributed SE_p between the two uppermost soil layers depending on their water contents. SE decreased below SE_p as the soil dried. Daily actual transpiration (T) was predicted using the method reported by Woodruff and Tonks (1983) but with some allowance for rooting depth changes with crop development. This method generated the potential water uptake (U_p) of the crop for any given soil water condition. T was taken as the minimum of T_p and U_p. Hence, when soil water was limiting T decreased below T_p. In such water-limiting situations the stress index (WSI) used in the crop growth sub-model was calculated as the ratio T/T_p.

Runoff and infiltration were predicted from daily rainfall using an approach similar to that reported by Boughton (1968). After recharging the surface layer, the infiltration amount decreased as the antecedent moisture content of the second layer increased. This was over-ridden by an algorithm accounting for soil cracking when the soil layers were sufficiently dry. In such instances some water was infiltrated directly into the deeper layers. The procedure was empirical but derived from infiltration studies reported by Shaw and Yule (1978).

Nitrogen sub-model

This sub-model was used throughout the crop phase to derive the nitrogen stress index (NSI) needed in the crop growth sub-model. Nitrogen dynamics in the soil throughout the fallow phase were not modelled. It was assumed that at the time of planting, 7.7 g m^{-2} of nitrogen had mineralized to available form during the fallow phase. This amount was determined from measurements on the relevant soil type (unpublished data, QWRI). No attempt was made to incorporate effects associated with long-term continuous cropping, such as the run-down of soil organic matter.

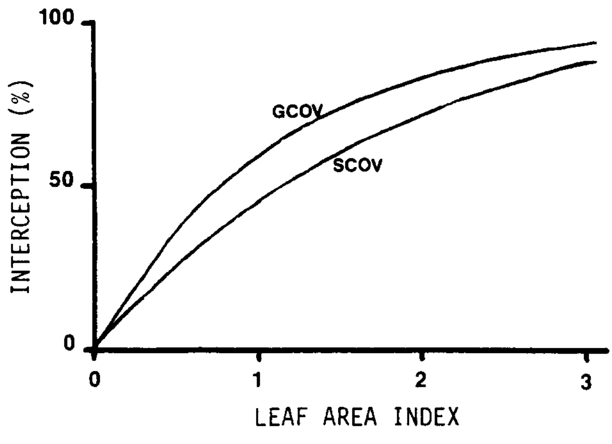

Fig. 5. Energy interception functions, $SCOV$ and $GCOV$, for determining potential soil evaporation and potential transpiration, respectively.

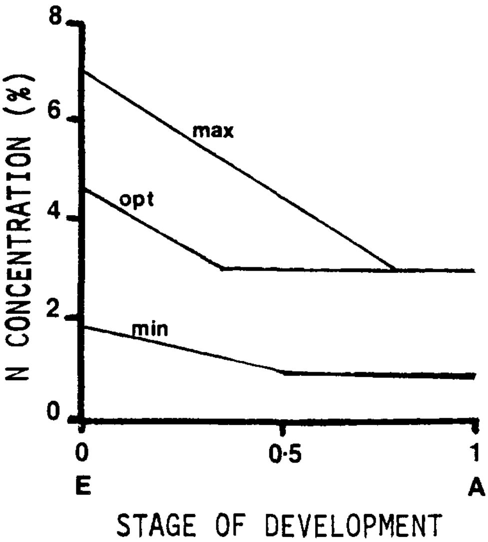

Fig. 6. Maximum (max), optimum (opt), and minimum (min) plant nitrogen concentration as a function of stage of development. (E = emergence; A = anthesis.)

During the crop phase, crop demand for nitrogen (*DEMN*) was related to potential *CGR* and required plant nitrogen concentration. Three levels of plant nitrogen concentration (maximum (*MAXN*), optimum (*OPTN*), and minimum (*MINN*)), each dependent on stage of development (Fig. 6) were determined using data from relevant experiments (Strong, 1981; Woodruff, 1984). Uptake of nitrogen from the soil (*UPTN*) was related to transpiration amount and available nitrogen concentration in each soil layer. *NSI* was then determined as the ratio *UPTN*/*DEMN* although some allowance was made for redistribution within the plant from a nitrogen excess pool which accumulated when uptake was greater than that required to meet the optimum. This approach was similar in concept to that reported by Angus and Moncur (1985).

Available nitrogen in each soil layer was redistributed throughout the soil profile on infiltration events, according to the amount of water movement between layers and nitrogen concentration in the water. The amount removed by the crop (*UPTN*) was deducted from the appropriate layers and thus, a simple balance of available soil nitrogen was maintained.

Planting criterion sub-model

In the study area wheat is usually planted after the summer fallow, between early May and late July, depending on occurrence of planting rains. Farm records covering a 20-year period of continuous cropping were obtained from a property near Roma. A criterion to predict time of planting, based on amount of rain and time of year, was developed from these records (Table I).

An additional requirement of nine rain-free days after the planting rainfall

TABLE I

Criterion to predict time of planting

Day of year	Rainfall required for planting
< 105	no planting
105–120	3-day total > 20 mm
120–166	1-day total > 16 mm or
	2 to 6-day total > 20 mm
166–222	1 to 6-day total > 16 mm
> 222	no planting

event was imposed to account for the need for some soil drying to allow access of planting equipment, and for the likely spread of planting over a number of days. The fit of this criterion to the 20-year record is shown in Fig. 7. The criterion shows that the farmer was prepared to accept more marginal planting conditions as the feasible planting period progressed.

In this region, desired planting time is such that flowering will occur immediately after the frost-prone period. The average last frost occurs about mid-August (Rosenthal and Hammer, 1978) although this will vary throughout the region. To ensure flowering after this time, late-maturing varieties are planted on rains early in the season, and early-maturing varieties are planted on later rains. Development rates of these types have been presented in Fig. 4. The switch between maturity types occurs about early June and in this study this was taken as day number 152.

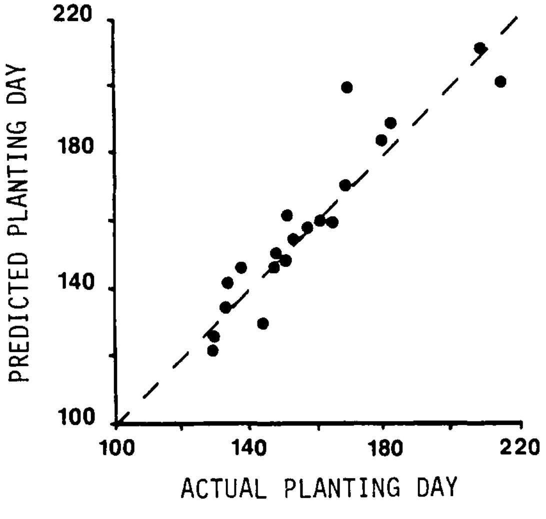

Fig. 7. Comparison of actual and predicted time of planting using planting criterion defined in text.

Model testing

Many components of the model had been tested during their development and although many of the functions involved were empirical in nature, they were biologically sensible and usually spanned a broad range of conditions. Little data from the study region were available for further testing of model components. However, the same 20-year sequence of farm records referred to above was available for use as an overall test of the model. The records of area planted, varieties used, and paddock yields were adequate for reliably estimating grain yield per unit area from a known variety in 16 of the 20 years. Daily rainfall records and relevant soil characteristics were available. The model was used to simulate this 20-year period from a starting point after an extended rainy period when it was assumed the soil profile would be fully wet. Simulated and actual yields were compared for the 16 years where records were reliable.

Simulation studies

The model was used to simulate continuous wheat cropping at a number of sites throughout the Maranoa and Warrego region. Long-term records of daily rainfall were available from the Bureau of Meteorology and average pan evaporation and temperature records from the Austclimdata data base (Keig and McAlpine, 1969). The 92-year period 1889–1981 was used. Soil conditions described in the soil water sub-model were assumed at all sites. Sites were chosen to give an east-west transect and two north-south transects through the region. Sites along the east-west transect were Dalby, Miles, Roma, Mitchell, and Charleville. The first two sites are east of the study region in established cropping areas with higher rainfall. They were included for comparative purposes. The remaining three sites and rainfall gradient associated with them are shown in Fig. 2. The first north–south transect was in the eastern part of the study region, the sites being Roma, St. George, and Dirranbandi (Fig. 2). The other north–south transect was in the western part of the study region, the sites being Tambo, Charleville, and Cunnamulla (Fig. 2).

Analysis of simulated yield sequences

For each of the nine sites, a 92-year yield sequence was generated by the simulation study. Cumulative probability distributions of grain yield were constructed from the yield sequences. This enabled estimation of risk associated with cropping and comparisons among sites, and thus provided the basis for estimating reliability of cropping throughout the region.

Trends in the yield sequences at each site were examined by plotting the progression with time of the accumulated deviation from the overall site mean yield. These graphs were compared with similar analyses of long-term seasonal rainfall reported by Russell (1981) and with analyses of factors associated with recent climatic change (Gilliland, 1981; Gilliland, 1982). These comparisons

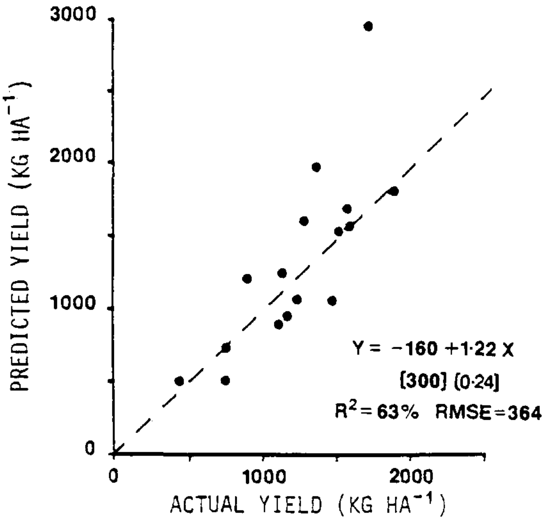

Fig. 8. Comparison of actual and predicted grain yields for model test. Numbers in brackets are standard errors of regression coefficients.

were used to aid interpretation of the estimates of reliability of cropping in this region and as a basis for discussion of possible future trends.

RESULTS AND DISCUSSION

Model testing

Comparison of predicted with actual grain yields for the farm near Roma, where a 20-year sequence of farm records was available, is presented in Fig. 8. A good correlation was found for the 16 years of available yield records. One serious outlier, where predicted yield was much greater than actual yield, occurred. This may have been associated with yield reduction caused by frost incidence around anthesis or disease incidence, as these factors were not incorporated in the model. It was considered that the fit was adequate to enable use of the model in examining reliability of cropping in the study region via simulation studies.

Simulated yield sequences

A simulated yield sequence was generated for each site. The sequence for Roma is shown in Fig. 9. Relevant attributes of the yield sequences for the three transects of sites are given in Table II.

For sites on the east-west transect, yield level decreased, variability increased, and years missed increased from east to west along the decreasing rainfall gradient. Sites along each of the north-south transects were similar,

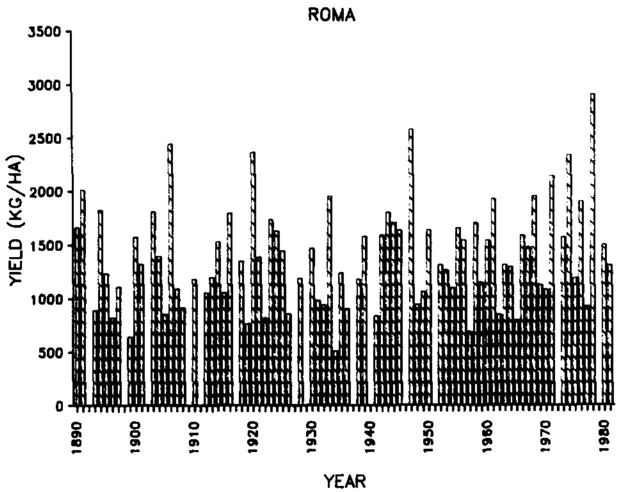

Fig. 9. Simulated yield sequence for continuous wheat cropping for the period 1889–1981 at Roma.

possibly excepting St. George in the first north-south transect. At this site fewer missed years occurred than at either Roma or Dirranbandi, so the mean yield was higher. This may have been associated with a localized effect on planting rain reliability, as seasonal and annual rainfall amounts were similar at the three sites along this transect.

TABLE II

Attributes of yield sequences for the three transects of sites

Site	Yield attribute		
	Mean ($kg\,ha^{-1}$)	CV[a] (%)	Years missed[b] (%)
(i) East–West Transect			
Dalby	1685	41	4.3
Miles	1474	47	7.5
Roma	1192	56	15.2
Mitchell	1018	57	12.9
Charleville	1005	65	18.3
(ii) First North–South Transect			
Roma	1192	56	15.2
St. George	1324	55	8.7
Dirranbandi	1254	60	16.1
(iii) Second North–South Transect			
Tambo	873	69	19.6
Charleville	1005	65	18.3
Cunnamulla	937	70	16.1

[a]CV is the coefficient of variation.
[b]Years missed includes both failing to plant and planting with subsequent crop failure.

Cumulative probability distributions of grain yield (Fig. 10) were constructed from the yield sequences. The curves were plotted as the probability of exceeding any particular yield level. Probability decreased from east to west for sites on the east-west transect. Plots for sites on the first and second north-south transects differed little from those for Roma and Charleville (Fig. 10), respectively.

Risk associated with cropping throughout the study region was quantified by the probability curves. For example, if a yield of 1000 kg ha^{-1} is required to meet development and operating costs, and provide an acceptable profit, then likelihood of achieving this yield can be determined. Probability of exceeding this yield level in any given year decreased from about 90% at Dalby and 75% at Miles (the two sites in the established cropping region to the east) to about 65% at Roma and 50% at both Mitchell and Charleville. Hence, reliability of long-term cropping at each location can be determined.

The yield probability distributions can be used to calculate the expected value of yield, thus providing, in conjuction with associated cost information, a basis for economic analysis of long-term cropping. But as well as long-term reliability, impact of yield sequences on survival in the short-term must be considered, as many of the major costs of development are incurred at the onset. The probability distributions can also be used to generate random yield sequences for such an analysis if annual yields in the series are random and independent. Statistical tests (turning points; phase length; rank; (Kendall, 1973) on the simulated yield sequence for Roma indicated that annual yields were random and independent.

Economic analyses of this type, for both short- and long-term, have been conducted using these results (Whan et al., 1984)., They found that wheat-growing in the Maranoa and Warrego was profitable in the long-term and there was a low probability of financial failure in the short-term, despite variability of income. When considering this outcome it is necessary to be aware of assump-

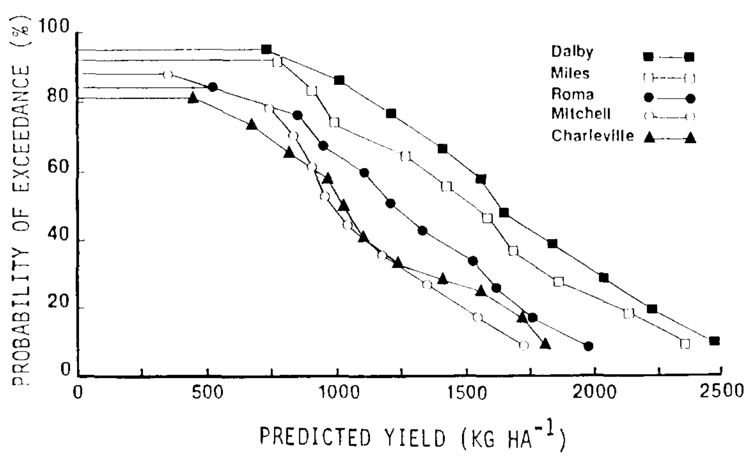

Fig. 10. Cumulative probability distributions of grain yield for sites along the east–west transect.

tions underlying the analysis. The simulation studies were relevant only to the one soil type used; they did not consider any detrimental effects of frost at flowering or of continuous cropping; some parts of the model have not been tested extensively (e.g. soil water balance through the summer fallow period); and there were some factors not incorporated in the economic analysis (e.g. considerations associated with a mixture of enterprises and provision for soil erosion prevention measures). Whilst these factors limited realism of the analysis, it does appear that expansion of wheat cropping in this region is feasible and can be expected over time.

Yield sequence trends and recent climatic change

Although no statistically significant dependence was found in the yield sequences, long-term patterns may still exist as the length of the sequences may not have been adequate for their detection statistically. Russell (1981) reported long-term patterns in seasonal rainfall for the Australian continent by plotting time series of accumulated deviations from the mean for the period 1895–1974. Plots of this type will start and end at zero with rises and falls being associated with above average and below average years. Russell grouped locations according to similarity of these plots using pattern analysis, and geographical distribution of groups was mapped. For summer (October to March) rainfall, Russell's groups B and D (Fig. 11) were relevant to the Maranoa and Warrego region. For sites used in the east–west transect in this study, the eastern sites were located in the area associated with group D and the western sites with group B.

Yield sequences for each site on the east–west transect were plotted similarly as time series of accumulated deviations from mean yield for comparison. Plots for Dalby, Roma, and Charleville are shown in Fig. 12. The plots for Miles and Mitchell were similar to those for Dalby and Charleville respectively. The eastern sites (Dalby, Miles, and Roma) show a pattern broadly similar to the

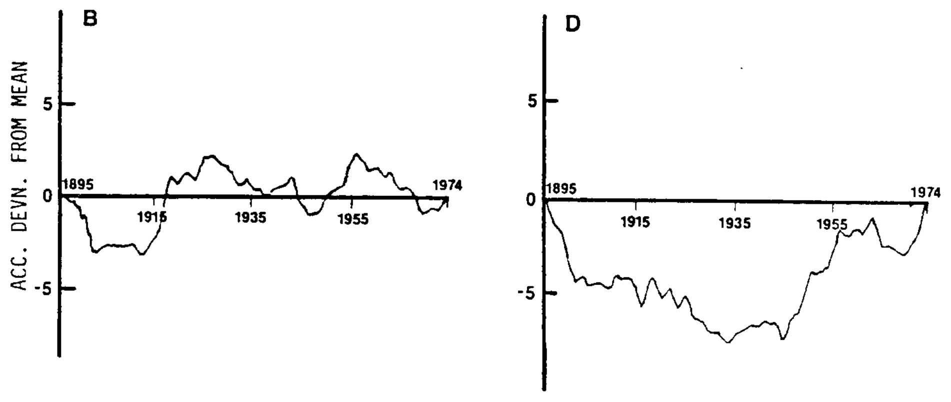

Fig. 11. Accumulated deviation from mean summer rainfall (groups B and D of Russell, 1981).

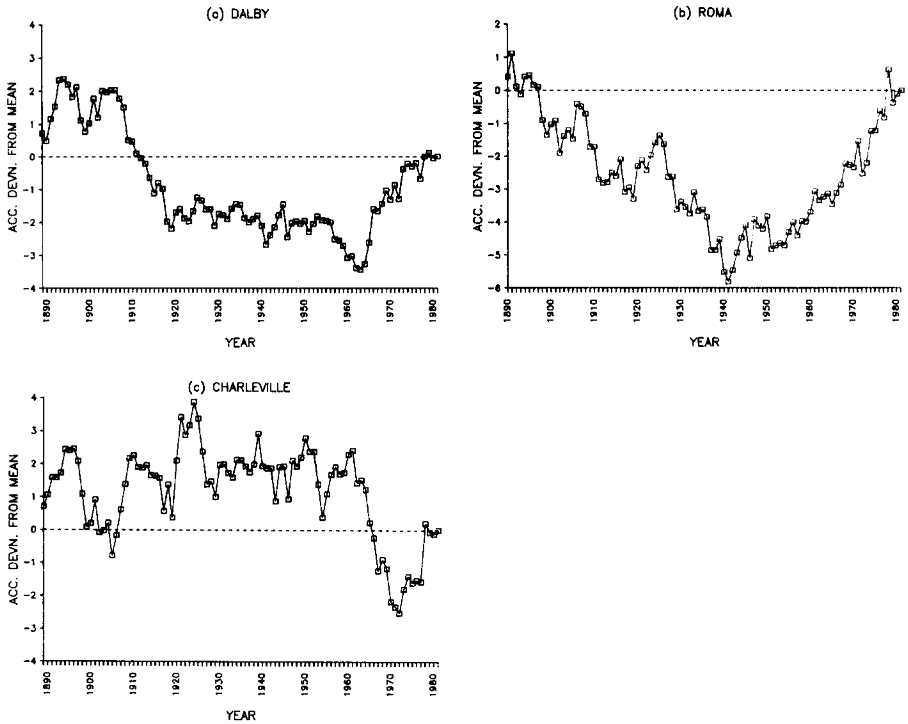

Fig. 12. Accumulated deviation from mean predicted yield for sites on the east–west transect: (a) Dalby, (b) Roma, and (c) Charleville. The accumulated deviation is scaled as the number of means above or below the long-term mean.

summer rainfall trend (group D) in that there is a decline and then increase centred about 1940, although, as expected, there is less similarity at the detailed level. For western sites (Mitchell and Charleville), yield trends also show a pattern broadly similar to the summer rainfall trend (group B), although it is quite different to the pattern found for eastern sites. The broad association of winter crop yield trends with summer rainfall trends can be explained by reliance on recharge of water stored in the soil profile during the summer fallow as noted by Nix (1975).

A number of phenomena on the Australian continent have been associated with a possible climatic change around 1940. These include sand movement and winds (Ward and Russell, 1980) and floods and river channel changes (Erskine and Bell, 1982). Barry (1978) has reviewed recent climatic fluctuations and noted that Kraus (1963) first reported the change in rainfall patterns around 1940. Barry further noted that this pattern however, was not general over the continent. This was also clearly shown by Russell (1981). However, analysis of the spatially-variable patterns by Pittock (1975) suggested that regional precipitation changes could be related to changes in the so-called Southern Oscillation Index and hence to changes in amplitude of the standing wave pattern

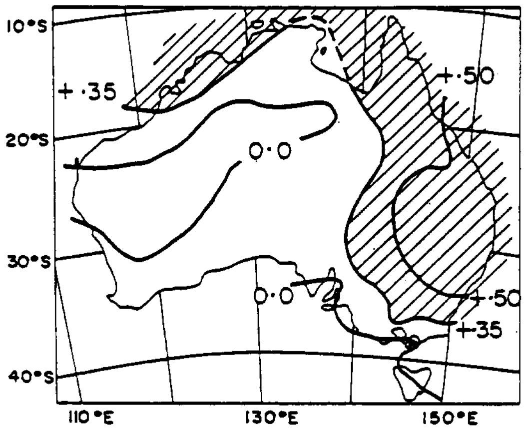

Fig. 13. Isopleths of equal correlation coefficient (R) between the annual mean Southern Oscillation Index and district mean annual rainfall. Data for years 1941–70 inclusive. R = 0.35 significant at 95% level (after Pittock, 1975).

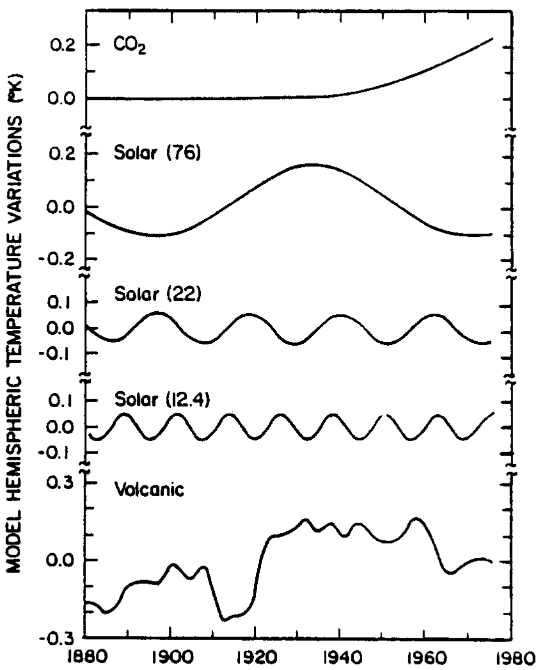

Fig. 14. Hemispheric temperature variations associated with external climate forcing factors (CO_2, solar variability, volcanic aerosols) for a climate model fitted to the northern hemisphere temperature record (after Gilliland, 1982).

of general circulation of the atmosphere (Fig. 13). Thus, a single cause for the range of patterns observed was possible.

Gilliland (1981) found a 76-year cycle of solar radius variation and linked this to recent climatic change using a climate model which incorporated the external climate forcing factors of CO_2, solar variability, and volcanic aerosols (Fig. 14) (Gilliland, 1982). Whilst impact of assumptions and statistical uncertainties of Gilliland's analysis have been questioned (Enting et al., 1984), the model remains physically reasonable. Gilliland (1982) reported that the last maximum of solar radius occurred in 1911 but he also found a 24-year lag for temperature response of the Earth which reached a maximum about 1935. This lag was associated with the 19-year lag of solar luminosity on solar radius and a further 5-year lag for the Earth's climate system response.

This solar radius cycle may be the driving force for variation in amplitude of the standing wave pattern of general circulation of the atmosphere, and hence, the rainfall patterns and yield patterns observed. The general cooling since about 1935 has been associated with increased rainfall in some regions (e.g. eastern sites in this study). The implication is for reversal of this trend after about 1975, until about 2015, with a general warming and associated decline in rainfall and yield. Likely impact of the cycle is more relevant to established cropping regions east of the study region and the eastern section of the study region, as these areas reflect this cycle in their rainfall and yield patterns. The impact is not as severe in the western part of the study region, where likely expansion will occur, as rainfall and yield patterns are affected in a manner which does not mimic the solar cycle.

This scenario is confounded by recent anthropogenic increase in atmospheric CO_2 levels and associated increase in temperature of the Earth. This factor was considered by Gilliland (1982) in his study of recent climatic change. Until recently (about 1975), effects of the solar cycle (i.e. a general cooling) were acting in the opposite direction to the CO_2 influence (Fig. 14). However, they are now both operating in the direction of warming. Hence, a more rapid increase in temperature is anticipated. This implies a more rapid return to the temperature levels similar to the previous maximum around 1935. This may be associated with decreasing rainfall and crop yield as in the previous period of warming (i.e. 1900 to 1935). However, until links between general climatic forcing factors (i.e. solar cycle and CO_2 levels) and relevant components of general circulation of the atmosphere can be better predicted, consequences of the anticipated hastening of warming remain unclear.

This analysis indicated that westward expansion of wheat cropping in the Maranoa and Warrego region was assisted by a series of favourable years that were possibly associated with recent climatic change. Links between climatic forcing factors and general circulation are not understood sufficiently well to enable prediction of effects on climate of likely changes in forcing factors. Hence, at this time, decisions for the future would be best based on the probability distributions presented (Fig. 10) and discussed above. However, an awareness of the possible impact of continuing climate change should be generated. This analysis indicated that this may be more relevant to the established cropping region than to the regions further west.

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