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LARGE AREA CROP INVENTORY EXPERIMENT (LACIE)

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AN INDEX FOR ESTIMATING WHEAT YIELD IN AUSTRALIA

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Houston, Texas 77058

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An Index for Estimating Wheat Yield in Australia

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An Index for Estimating Wheat Yield In Australia

C. M. Sakamoto[1]

INTRODUCTION

Indices utilizing meteorological data have provided better estimates of crop yields than direct use of monthly temperature and precipitation data (Nix and Fitzpatrick, 1969; Sakamoto and Jensen, 1975; Baier and Robertson, 1968). These indices also provide a single variable that combines the effects of several meteorological variables. Perrin and Heady (1975) used a moisture index they referred to as "M," which was defined as the difference between the actual evapotranspiration and the "climatically appropriate" evapotranspiration. Evapotranspiration was estimated by the procedure of Palmer (1965). Perrin and Heady found that the index M explained more of the yield variation for wheat than either the absolute level of moisture deficiency (ET-PET) or the estimated soil moisture. Sakamoto and Jensen (1975), in their work with Palmer's moisture anomaly index "Z," found that this index, together with temperature departure, explained more of the yield variation than using the ratio of ET/PET or accumulated soil moisture.

The purpose of this study is to determine the feasibility of using monthly meteorological information into useful indices to estimate wheat yields in Australia. The meteorological data, including temperature and precipitation, are used in an index, called "Z," a moisture anomaly for a given area.

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The use of monthly data is appealing because it is readily available over the world. Furthermore, monthly temperature and precipitation are easier to estimate when missing for an area. On the other hand, aggregated monthly data suffer from the obvious inability of being sensitive to short period fluctuations or episodes that occur over a day or so. These events, in turn, can be detrimental to yield and could lead to spurious estimates. In spite of this disadvantage, however, much information can be extracted from the use of these longer period data.

THE Z-INDEX

Monthly temperature and precipitation are used in an algorithm that derives the Z-index. This is defined as:

$$Z = dk \tag{1}$$

where:

$$d = P - \hat{P} \tag{2}$$

and P is the observed precipitation while $\hat{P}$ is the "climatically appropriate" precipitation. $\hat{P}$ is further estimated by:

$$\hat{P} = \widehat{ET} + \hat{R} + \widehat{RO} - \hat{L}. \tag{3}$$

Evapotranspiration $\widehat{ET}$, recharge $\hat{R}$, runoff $\widehat{RO}$, and loss $\hat{L}$ are obtained by multiplying its potential value (PET, PR, PRO, PL) by the coefficient which is the ratio of average $\overline{ET}$, $\overline{T}$, $\overline{RO}$ or $\overline{L}$ by its average potential values; that is, $\alpha = \overline{ET/PET}$, $\beta = \overline{R/PR}$, $\gamma = \overline{RO/PRO}$, $\sigma = \overline{L/PL}$. Climatically appropriate evapotranspiration, recharge, runoff, and loss are then determined as: $\widehat{ET} = \alpha \cdot PET$, $\hat{R} = \beta \cdot PR$, $\widehat{RO} = \gamma \cdot PRO$, and $\hat{L} = \sigma \cdot PL$, respectively.

Soil moisture depletion is based on evapotranspiration (ET) estimates and is determined by the following:

$$(ET)_n = \frac{(S)_{n-1}}{AWC} \{(PET)_n - (P)_n\} + (P)_n \tag{4}$$

where:

$(ET)_n$ = "actual" evapotranspiration,

$(S)_{n-1}$ = available moisture at end of n-1 months,

AWC = maximum water holding capacity,

$(P)_n$ = precipitation for month n,

$(PET)_n$ = potential evapotranspiration for month n.

Determination of recharge, runoff and loss is through a hydrologic accounting procedure developed by Palmer (1965). Briefly, this procedure utilizes a two-layer soil profile and assumes that the surface layer holds one inch of water and the lower layer holds the remaining amount. Moisture is lost at a potential rate from the surface layer until all moisture is lost in that layer; i.e.,

$$L_s = (PET - P) \text{ or } S_s' \quad (5)$$

where:

L_s = soil moisture loss from surface layer,

S_s' = stored available moisture in surface layer.

After all the surface moisture is lost, moisture is extracted from the lower layer as a percent of available soil moisture (see Figure 1). Precipitation adds to the top layer until field capacity is reached before the lower layer is recharged. Runoff is assumed to occur only after both layers have reached field capacity, although this assumption may not be entirely satisfactory.

The amount of moisture lost from the underlying layer is determined by the following relationship:

$$L_u = (S_u/AWC)\ (PET - P - L_s) \quad (6)$$

where:

L_u = soil moisture loss from underlying (lower) layer,

S_u = available soil moisture in the lower layer at the beginning of the month,

AWC = water holding capacity (combined layers),

PET = potential evapotranspiration based on Thornthwaite's (1948) procedure,

P = precipitation for the month,

L_s = soil moisture loss from upper (surface) layer.

In the accounting procedure, if the soil moisture content in both layers is zero, evapotranspiration, ET, is assumed to be equal to

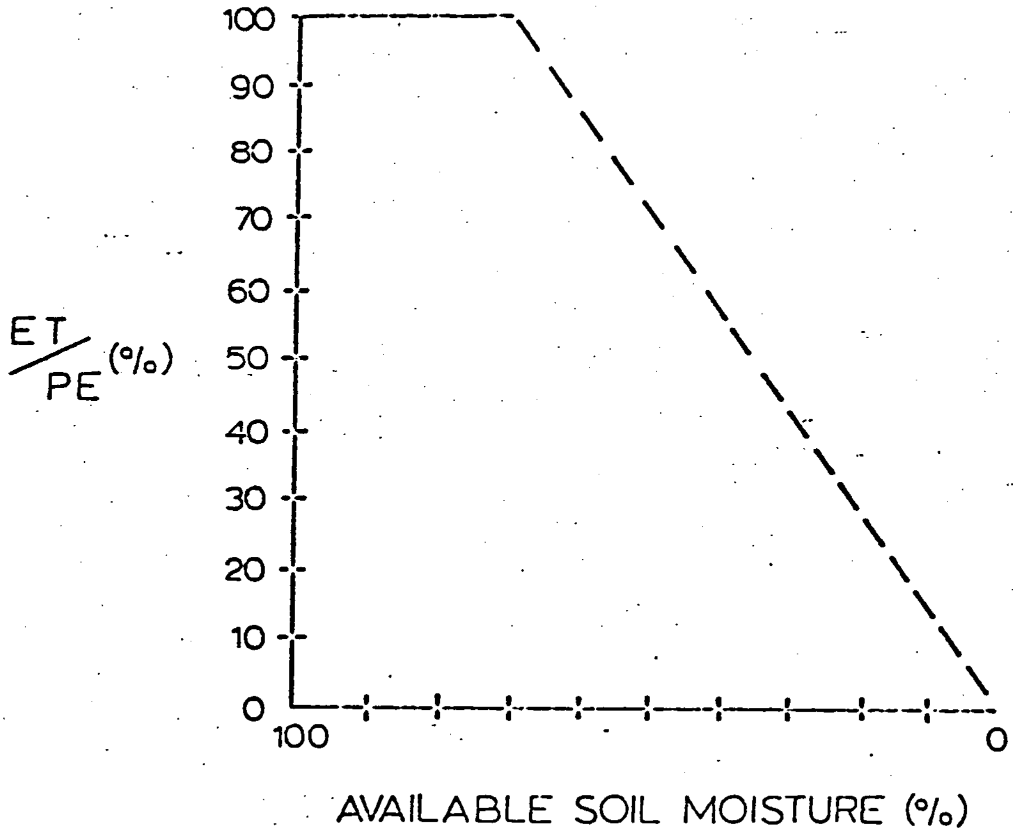
100
90
80
70
60
50
40
30
20
10
0
ET/PE (%)
100
0
AVAILABLE SOIL MOISTURE (%)

Figure 1

precipitation; i.e., ET = P. The potential values, including potential evapotranspiration PET, potential recharge PR, potential runoff PRO, and potential loss PL are used in the water balance procedure and are defined as follows:

$$PR = AWC - S' \tag{7}$$

where:

PR is the amount of moisture required to bring the soil to field capacity and AWC is the available water capacity. S' is the amount of available moisture in the two layers at the beginning of the period.

$$PL = PL_s + PL_u \tag{8}$$

where:

PL is the potential loss; i.e., the amount of moisture that could be lost from the surface (s) and underlying profile (u) provided precipitation is zero. It is further defined as PL_s = PE or S'_s whichever is smaller and PL_u is the potential loss from the underlying layer and is defined as:

$$PL_u = (PE - PL_s)\, S'_u/AWC.$$

In general, potential runoff PRO is equal to precipitation minus the amount that could be added to the soil or P-(AWC-S'). However, precipitation is not introduced for the development of potential runoff. For lack of a better way to handle this problem, potential runoff is defined as a function of soil moisture, the reason being that if soil moisture is high, potential runoff is likely to be large and vice versa. This reasoning seemed to have worked fairly well, according to Palmer (1965).

$$PRO = AWC - PR = S'. \tag{9}$$

Potential evapotranspiration is determined by the procedures developed by Thornthwaite (1948). To estimate potential evapotranspiration by Thornthwaite's procedure requires temperature and the heat index. The duration of daylight is used to adjust potential evapotranspiration as a portion of 12 hours. The basic equation is:

$$PET = (10T/I)^a \tag{10}$$

where;

I = heat index, which is the sum of the 12 monthly index i where $i = (T/5)^{1.514}$,

T = monthly temperature (°C),

a = an empirical exponent,

$= 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.79 \times 10^{-2} I + 0.49.$

The heat index I can alternately be estimated from the mean annual temperature t by the following relationship:

$$\ln I = 0.06798(t) + 3.199 \tag{11}$$

where t is in °C. The above relationship has been estimated from the data of Palmer and Havens (1958).

The variable k is the average demand and supply coefficient which varies with the local climate. It is a measure of the local significance of the moisture departures. It is initially estimated by an empirical relationship for month i by:

$$k_i' = 1.5 \log \{(\frac{\overline{PE_i} + \overline{R_i} + \overline{RO_i}}{\overline{P_i} + \overline{L_i}} + 2.80)/\overline{D_i}\} + 0.50 \tag{12}$$

where:

$\overline{D_i} = (\sum_{d=1}^{j} |d_{ij}|)/j$ for month i where j = number of year, i = 1 = January, 12 = December.

The final k is estimated by:

$$k_i = \frac{17.67\ (k_i')}{\sum_{i=1}^{12} (\overline{D}_i k_i')} \qquad (13)$$

k_i is therefore a weighting factor and has been derived from a range of climate including North Dakota in the north to Texas and Tennessee in the south and from Kansas in the west to Pennsylvania in the east. When used with d, the Z-index provides a comparable measure of moisture anomaly, the departure of the moisture climate from the average of the month.

DATA REQUIREMENTS

The basic meteorological inputs required to calculate the Z-index include monthly temperature and precipitation. These variables are used in the hydrologic accounting procedure as developed by Palmer (1965). The soil moisture budget also requires an estimate of the available water holding capacity for the profile. In the case of wheat, a profile of approximately four feet is assumed. This profile is, in turn, divided into two layers with one inch of water assumed in the top layer. For example, if six inches is determined as the available water holding capacity, the upper layer contains one inch while the lower layer has five inches.

To start the accounting process, the initial soil moisture content should be known. In practice, however, this is usually not known. Therefore, an estimate must be inserted to start the model so that once field capacity is reached (during the rainy season), the soil moisture status can be considered as reflecting the "current" situation. One could also start on a month subsequent to a rainy period. Since soil moisture, and also soil types vary greatly, the assigned soil moisture capacity must be considered a very general spacial value. Water holding capacity used in the program for Australia are shown in Table 1.

Table 1. Information for Use with the Z-Index Program

State-Division	Latitude (°S)	Mean Annual Temp. (°F)	Soil Water (inches) Heat Index	ULFC*	LLFC*	ULS*	LLS*
New South Wales	32.5	62.8	78.4	1.0	4.0	0.0	1.3
Central Plains	32.5	64.7	84.4	1.0	4.0	0.0	1.3
Central Slope	32.5	61.3	74.2	1.0	4.0	0.0	1.3
North Central Plains	30.0	66.9	91.6	1.0	4.0	0.0	1.3
Northwest Slope	30.0	63.5	74.9	1.0	4.0	0.0	1.3
Riverina	35.0	60.6	72.2	1.0	4.0	0.0	1.3
South Slope	35.0	59.7	69.8	1.0	4.0	0.0	1.3
Queensland	27.0	62.8	78.4	1.0	3.5	0.0	3.0
Downs-Dalby	28.0	62.8	78.4	1.0	3.5	0.0	3.0
West Downs	27.0	62.8	78.4	1.0	3.5	0.0	3.0
South Australia	34.0	61.5	74.7	1.0	3.0	0.0	1.0
Central	35.0	61.7	75.2	1.0	3.0	0.0	1.0
Lower North	33.5	61.3	74.2	1.0	3.0	0.0	1.0
Murray Mallee	34.5	61.5	74.7	1.0	3.0	0.0	1.0
Southeastern	36.0	59.2	68.4	1.0	2.0	0.0	1.0
Upper North	32.5	63.0	78.9	1.0	3.0	0.0	1.0
Western	33.5	62.4	77.3	1.0	3.0	0.0	1.0
Victoria	36.0	59.9	68.4	1.0	3.5	0.0	1.1
Mallee	35.0	61.2	73.7	1.0	3.0	0.0	1.0
Northern	36.5	59.7	69.8	1.0	3.5	0.0	1.1
Wimmera	36.5	58.6	67.0	1.0	3.5	0.0	1.1
Western Australia	32.0	62.8	78.4	1.0	2.2	0.0	0.8

* ULFC = Upper level moisture at field capacity.

LLFC = Lower level moisture at field capacity.

ULS = Upper level moisture at starting date (January 1940).

LLS = Lower level moisture at starting date (January 1940).

Daylength, as a fraction of 12 hours, is used in the potential evapotranspiration estimation. In this study, the daylength was input directly into the program (see Table 2). However, where several locations over the globe are of interest, a simple algorithm using only latitude and Julian date can be used to estimate the fraction of daylength from 12 hours.

DATA SOURCE

Monthly temperature and precipitation values were derived by arithmetically averaging records from selected stations within the meteorological district of the wheat growing area (personal communication, 1974). The meteorological districts were aggregated to areas that were similar to the area for which production and acreage data were on hand. Data from stations were provided by the Australian Bureau of Meteorology. Selected precipitation and temperature stations are shown by their approximate location in Figures 2 through 6. The number of stations included for each district as well as each state are shown in Table 3. The list of temperature stations are shown in Appendix A. More stations were included for precipitation because of its variable character. The period 1940-1972 was used to develop the model. The exception is in Queensland where a "division" model was developed from data for the period 1960-1972.

Wheat yield data were obtained from the Australian Bureau of Statistics for each state (private communication, 1975). Sufficient breakdown of the data permitted aggregation for a yield model based on "division" data similar to the crop reporting district in the United States. Twenty-two models are provided - a state model for each state and divisional models for the divisions in four of the five states. Western Australia has only a state model.

Table 2. Duration of Sunshine in Fraction of 12 Hours in Australia

State-Division	J	F	M	A	M	J	J	A	S	O	N	D
	MONTH											
N W Slope, NSW	1.20	1.03	1.06	.95	.92	.85	.90	.96	1.00	1.12	1.14	1.21
Central Slope, NSW	1.22	1.04	1.06	.94	.90	.83	.88	.95	1.00	1.13	1.16	1.23
Central Plains, NSW	1.22	1.04	1.06	.94	.90	.83	.88	.95	1.00	1.13	1.16	1.23
North Central Plains, NSW	1.20	1.03	1.04	.95	.92	.85	.90	.96	1.00	1.12	1.14	1.21
Riverina, NSW	1.23	1.04	1.06	.94	.89	.82	.87	.94	1.00	1.13	1.17	1.25
South Slope, NSW	1.23	1.04	1.06	.94	.89	.82	.87	.94	1.00	1.13	1.17	1.25
New South Wales	1.22	1.04	1.06	.94	.90	.83	.88	.95	1.00	1.13	1.16	1.23
Downs-Dalby, QLD	1.18	1.02	1.05	.96	.93	.87	.91	.97	1.00	1.11	1.13	1.19
West Downs, QLD	1.18	1.02	1.05	.96	.93	.87	.91	.97	1.00	1.11	1.13	1.19
Queensland	1.18	1.02	1.05	.96	.93	.87	.91	.97	1.00	1.11	1.13	1.19
Western Aust.	1.22	1.04	1.06	.94	.90	.83	.88	.95	1.00	1.13	1.16	1.23
Central S.A.	1.23	1.04	1.06	.94	.89	.82	.87	.94	1.00	1.13	1.17	1.25
Lower North, S. A.	1.22	1.03	1.06	.94	.90	.83	.88	.95	1.00	1.13	1.16	1.24
Upper North, S.A.	1.22	1.04	1.06	.94	.90	.83	.88	.95	1.00	1.13	1.16	1.23
Southeastern, S.A.	1.23	1.04	1.06	.94	.89	.82	.87	.94	1.00	1.13	1.17	1.25
Western, S. A.	1.22	1.03	1.06	.94	.90	.83	.88	.95	1.00	1.13	1.16	1.24
Murray Mallee, S. A.	1.23	1.04	1.06	.94	.89	.82	.87	.94	1.00	1.13	1.17	1.25
South Australia	1.23	1.04	1.06	.94	.89	.82	.87	.94	1.00	1.13	1.17	1.25

Table 2, Continued

State-Division	J	F	M	A	M	J	J	A	S	O	N	D
	MONTH											
Mallee, VIC	1.23	1.04	1.06	.94	.89	.82	.87	.94	1.00	1.13	1.17	1.25
Northern, VIC	1.24	1.05	1.06	.94	.88	.81	.86	.93	1.00	1.14	1.18	1.26
Wimmera, VIC	1.24	1.05	1.06	.94	.88	.81	.86	.93	1.00	1.14	1.18	1.26
Victoria	1.24	1.05	1.06	.94	.88	.81	.86	.93	1.00	1.14	1.18	1.26

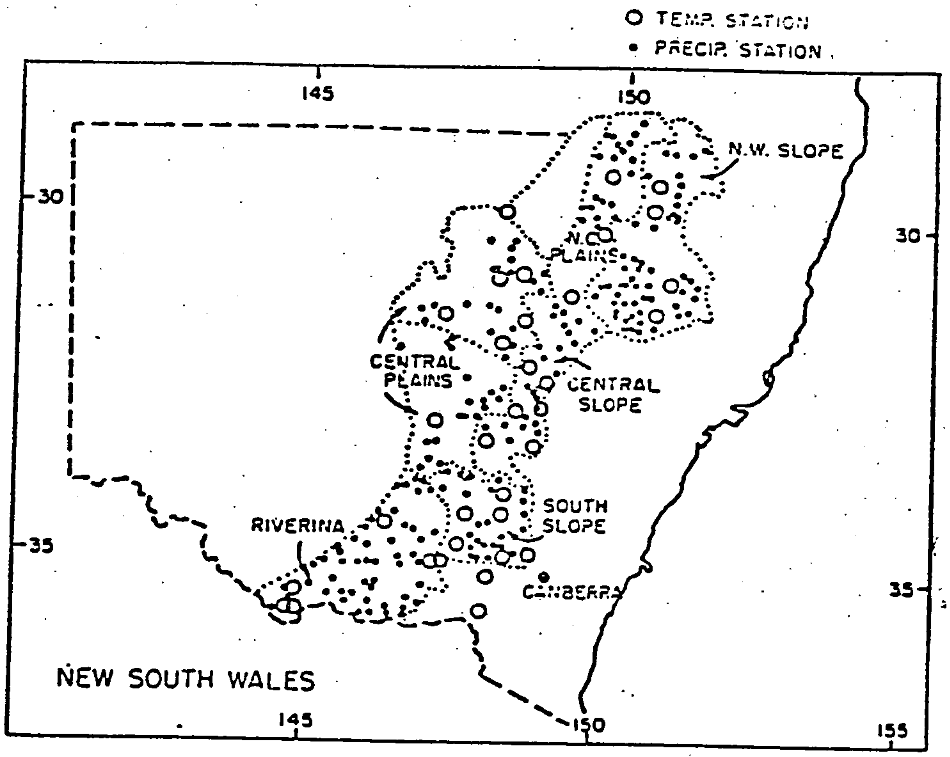

Figure 2. Wheat divisions in New South Wales, Australia showing distribution of temperature and precipitation stations.

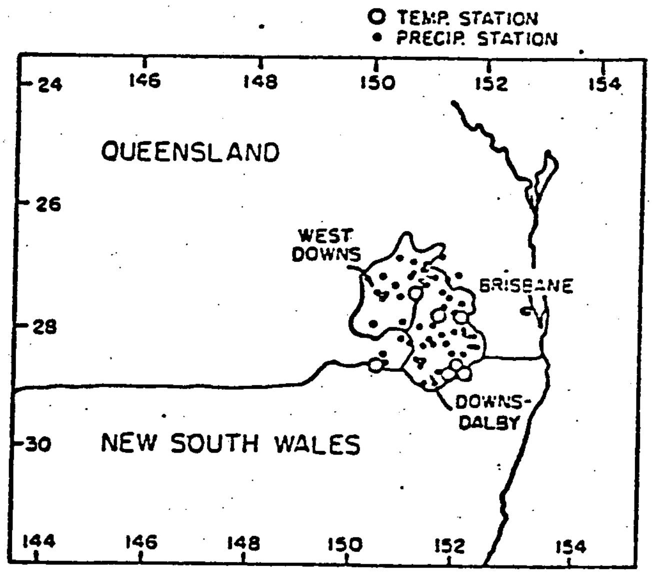

Figure 3. Wheat divisions in Queensland, Australia showing distribution of temperature and precipitation stations.

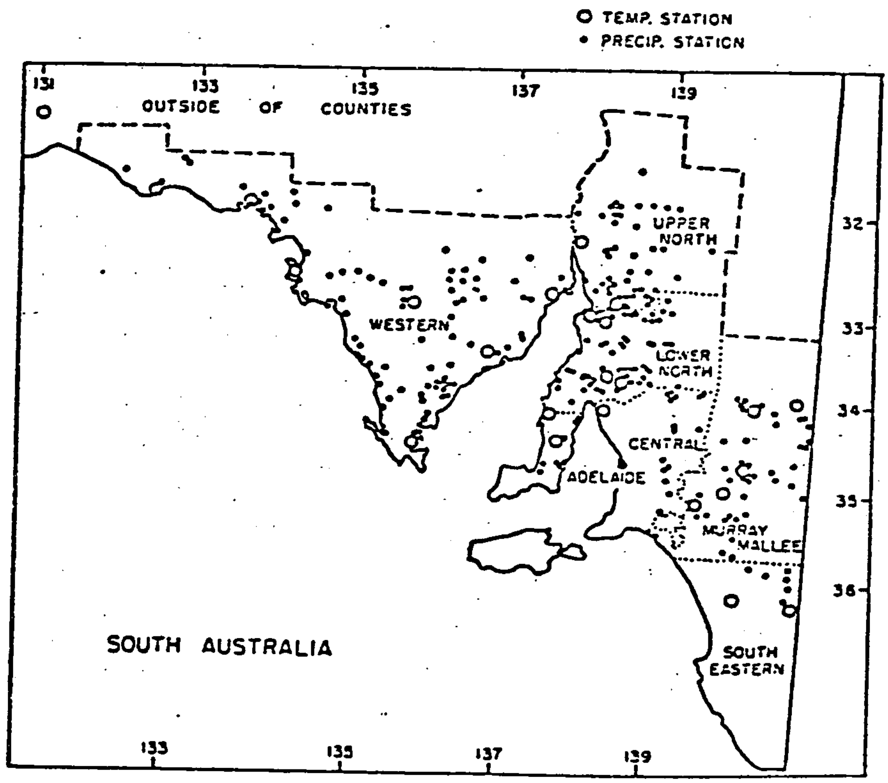

Figure 4. Wheat divisions in South Australia showing distribution of temperature and precipitation stations.

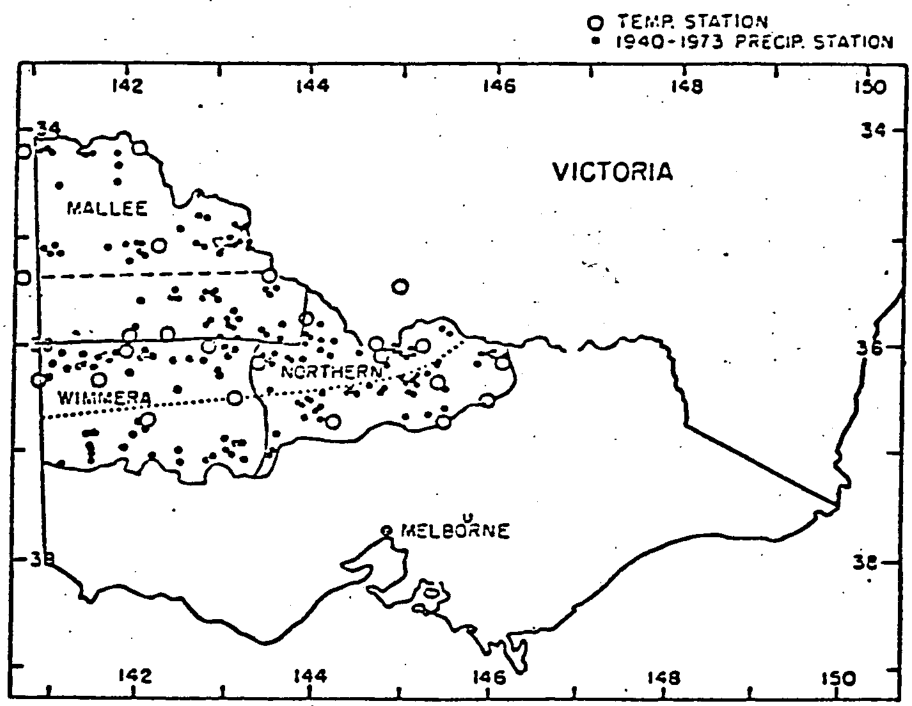

Figure 5. Wheat divisions in Victoria, Australia showing distribution of temperature and precipitation stations.

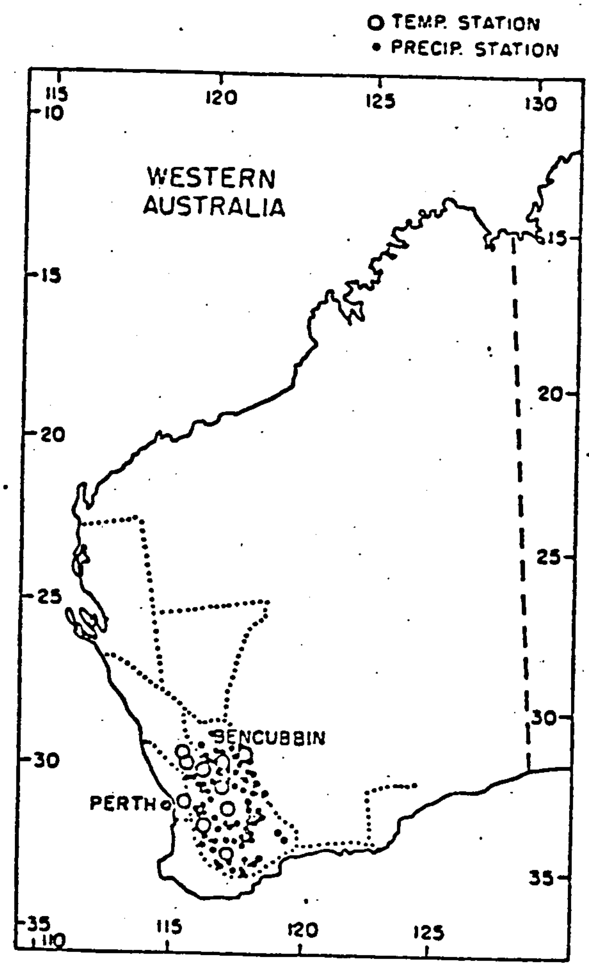

Figure 6. Wheat divisions in Western Australia showing distribution of temperature and precipitation stations.

Table 3. Number of Precipitation and Temperature Stations Used to Estimate Division Averages

State-Division	Precipitation	Temperature
New South Wales	270	34
Central Plains	51	6
Central Slope	31	7
North Central Plains	26	2
Northwest Slope	71	4
Riverina	56	7
South Slope	35	8
Queensland	63	9
Downs-Dalby	52	6
West Downs	9	3
South Australia	242	25
Central	20	2
Lower North	46	5
Murray Mallee	36	4
Southeastern	26	2
Upper North	47	4
Western	78	8
Victoria	217	30
Mallee	85	10
Northern	80	13
Wimmera	52	7
Western Australia	174	9

YIELD MODEL

Description of Model

Monthly Z-index as well as temperature departure from the 1940-1972 base period were used as variables in a multiple regression model. In addition, precipitation amounts (departure from normal) was included at harvesting (November, December) at locations where this variable was meaningful. For example, in Queensland, summer harvest is threatened by heavy downpour at harvest. Precipitation much above normal could decrease yield.

The Z-values were combined in some areas so that the effect of moisture was aggregated over a period greater than one month. This also permitted the treatment of this effect as a single variable. For example, Z-values for August, September, and October may be combined by a weighted average procedure. Weights are assigned to the months from June through November as a percent of water required at heading (October). The weights have been estimated from Figure 7 (after Richardson in Callaghan and Millington, 1957). Weights are as follows: June = .02; July = .08; August = .20; September = .50; October = 1.00; November = .83. The weighted averaging procedure was followed because this procedure revealed a better relationship with yield plots than with linear averaging. Further, the effect on yield with soil moisture deficiency is greatest at heading (Bauer, 1972).

The basic form of the equation is:

$$\hat{Y} = \alpha + \beta_1 T + \beta_2 \left(\frac{\sum_{i=1}^{n} Z_i \cdot W_i}{\sum_{i=1}^{n} W_i}\right) + \beta_3 \left(\frac{\sum_{i=1}^{n} Z_i \cdot W_i}{\sum_{i=1}^{n} W_i}\right)^2 \qquad (14)$$

$$+ \sum_{j=1}^{m} \gamma_j D_j + \sum_{j=1}^{m} \delta_j D_j^{\,2} + \sum_{j=1}^{k} \eta_j P_j + \varepsilon$$

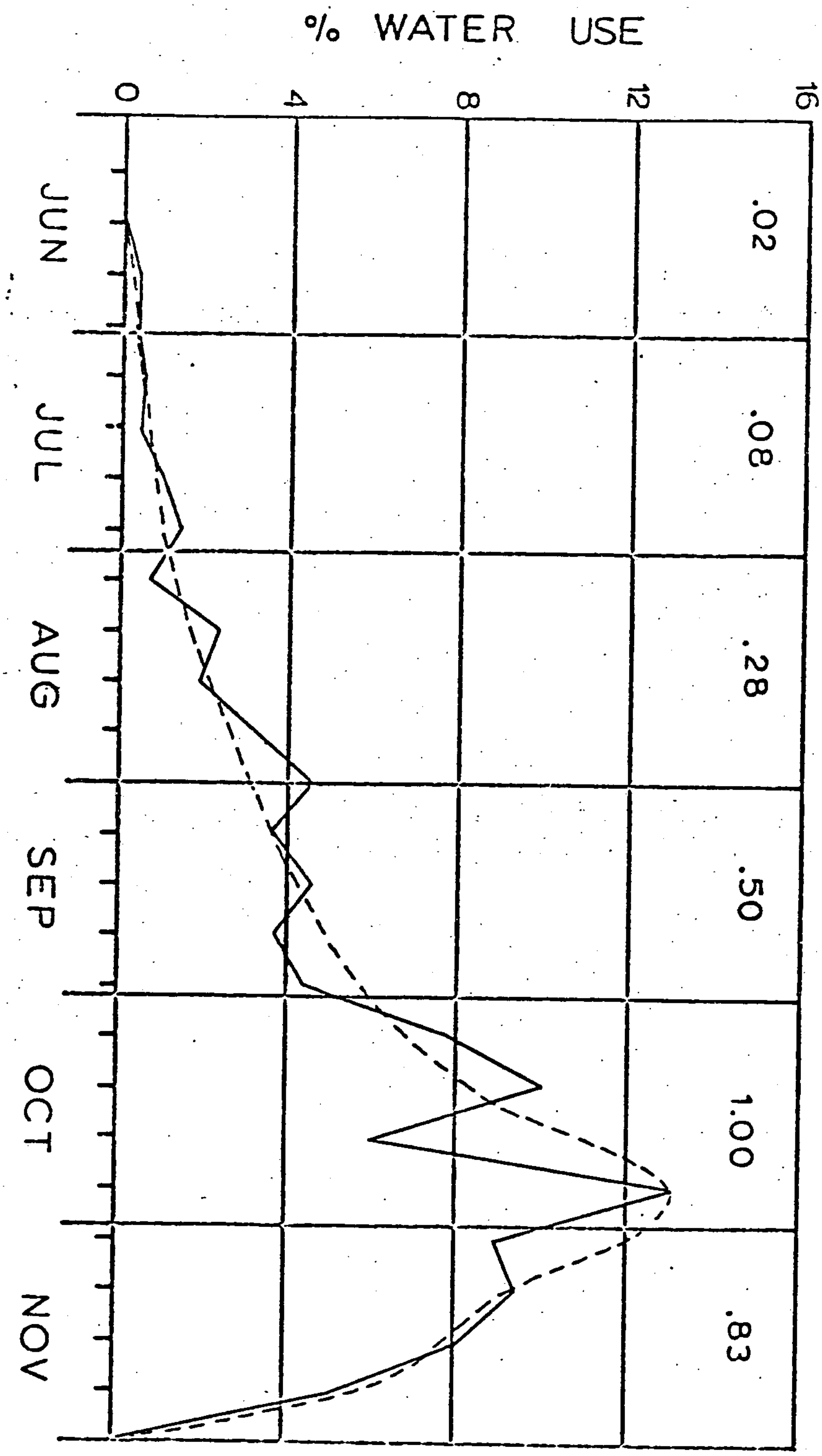

Figure 7

where:

$\hat{Y}$ = estimated yield,

α = constant,

T = trend 1940=1, 1941=2, ..., 1950=11, 1951=11, ...,

Z_i = Z-index for i number of months, i=1, 2, ..., n,

W_i = weights for month i to n (June through November only),

D_j = temperature departure from normal for month j, j=1 to m months,

P_j = precipitation departure from normal for month j=1 to k months,

β_1, β_2, β_3, γ_j, δ_j, η_j = coefficients of variables,

ε = unexplained error.

Each state or district included a variation of equation (14). Some models included only the linear term if the signs of the coefficient of the quadratic term seemed unrealistic. The variables and signs of the coefficient were selected after consideration of the approximate growth stage or activity (e.g., harvesting) involved, the plot of yield relationship with the variables and the reasonableness of the coefficient with known agronomic response to weather.

Both the value of the Z-index and the temperature departure, D, could be either negative or positive. If climatic conditions are close to "climatically appropriate" for a given area, Z and D will be close to zero. Large positive Z-values suggest wet conditions while large negative Z-index indicate dry conditions. The list of the models are shown in Table 4, while the models are presented in Appendix 3.

Truncation

Since it is desirable to estimate yield as early as possible prior to harvest, truncated models, usually beginning in May, have been developed. The index Z and D are assumed to be zero for the months subsequent to the

Table 4. List of Wheat Models for Australia with LACIE[1] Identification Code

	LACIE Code
Australian Wheat Models	06
Western Australia (State Model)	060105
South Australia (State Model)	060103
Division Models	
1. Western	06010301
2. Upper North	06010302
3. Lower North	06010303
4. Central	06010304
5. Murray Mallee	06010305
6. Southeastern	06010306
Victoria (State Model)	060104
Division Models	
1. Mallee	06010406
2. Wimmera	06010405
3. Northern	06010407
New South Wales (State Model)	060101
Division Models	
1. Central Plains	06010117 and 06010113
2. Northwest Slope	06010111
3. North Central Plains	06010116
4. Central Slope	06010112
5. South Slope	06010114
6. Riverina	06010117
Queensland (State Model)	060102
Division Models	
1. Downs-Dalby	0601020301
2. West Downs	0601020302

[1]LACIE - Large Area Crop Inventory Experiment

month of truncation. The models for all truncation are shown in the Appendix.

Technology

Inspection of the yield data series for all state and division data suggest that the trend of yield with time has stabilized since about 1950 (see e.g., Figure 8). "Technology," may include such factors as fertilizer application, crop management practices, use of bigger and better farm machinery, herbicide and insecticide application, etc. are assumed to be included in the trend term. Lacking the quantitative inputs of the effects of these factors into crop production, it is convenient to assign a linear trend as a surrogate for technology. The value of 1 is assigned to 1940 up to the value of 11 for 1950. After 1950, the linear trend assumes a value of 11. Although fertilizer usage has increased with time, the response to added fertilizer seems to have stabilized. As a rule wheat farmers in Australia apply superphosphate, except in Queensland and northern New South Wales where soils are not considered deficient in phosphates. Nitrogen is also applied in some areas. The rate of application ranges from about eight pounds per acre in Queensland and New South Wales to about 120 pounds per acre in South Australia (Bureau of Agricultural Economics, 1969).

DESCRIPTION OF THE WHEAT ZONES IN AUSTRALIA

Wheat is grown in the region south of latitude 25 degrees in the states of New South Wales, South Australia, Queensland, Victoria and Western Australia (Figure 9). Average annual precipitation ranges from 5 to 15 inches (Peterson, 1965). In these areas, two distinct patterns of precipitation distribution are evident (Figure 10). In Western Australia, Victoria

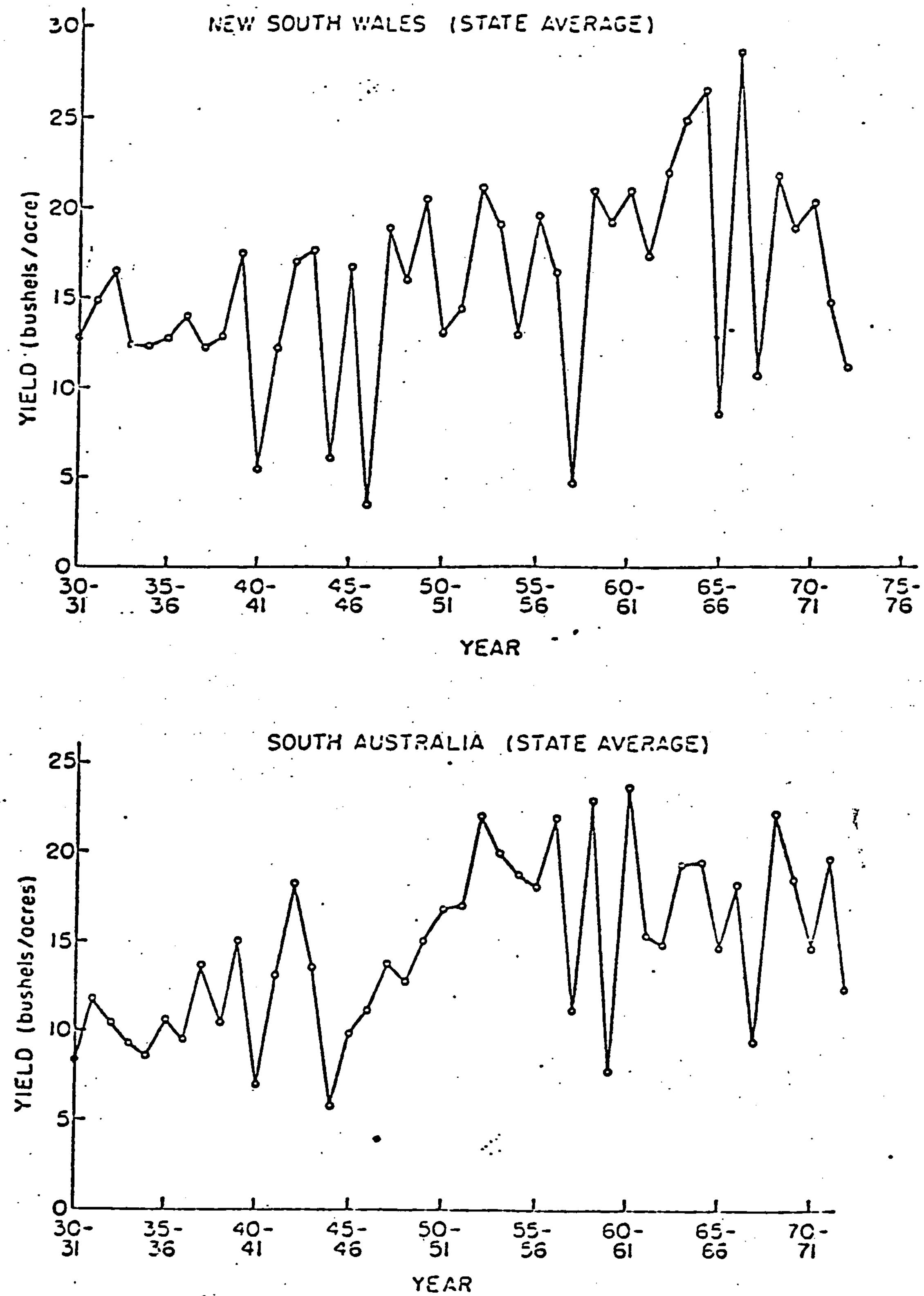
NEW SOUTH WALES (STATE AVERAGE)
YIELD (bushels/acre)
30
25
20
15
10
5
0
30-31
35-36
40-41
45-46
50-51
55-56
60-61
65-66
70-71
75-76
YEAR
SOUTH AUSTRALIA (STATE AVERAGE)
YIELD (bushels/acres)
25
20
15
10
5
0
30-31
35-36
40-41
45-46
50-51
55-56
60-61
65-66
70-71
YEAR

Figure 8

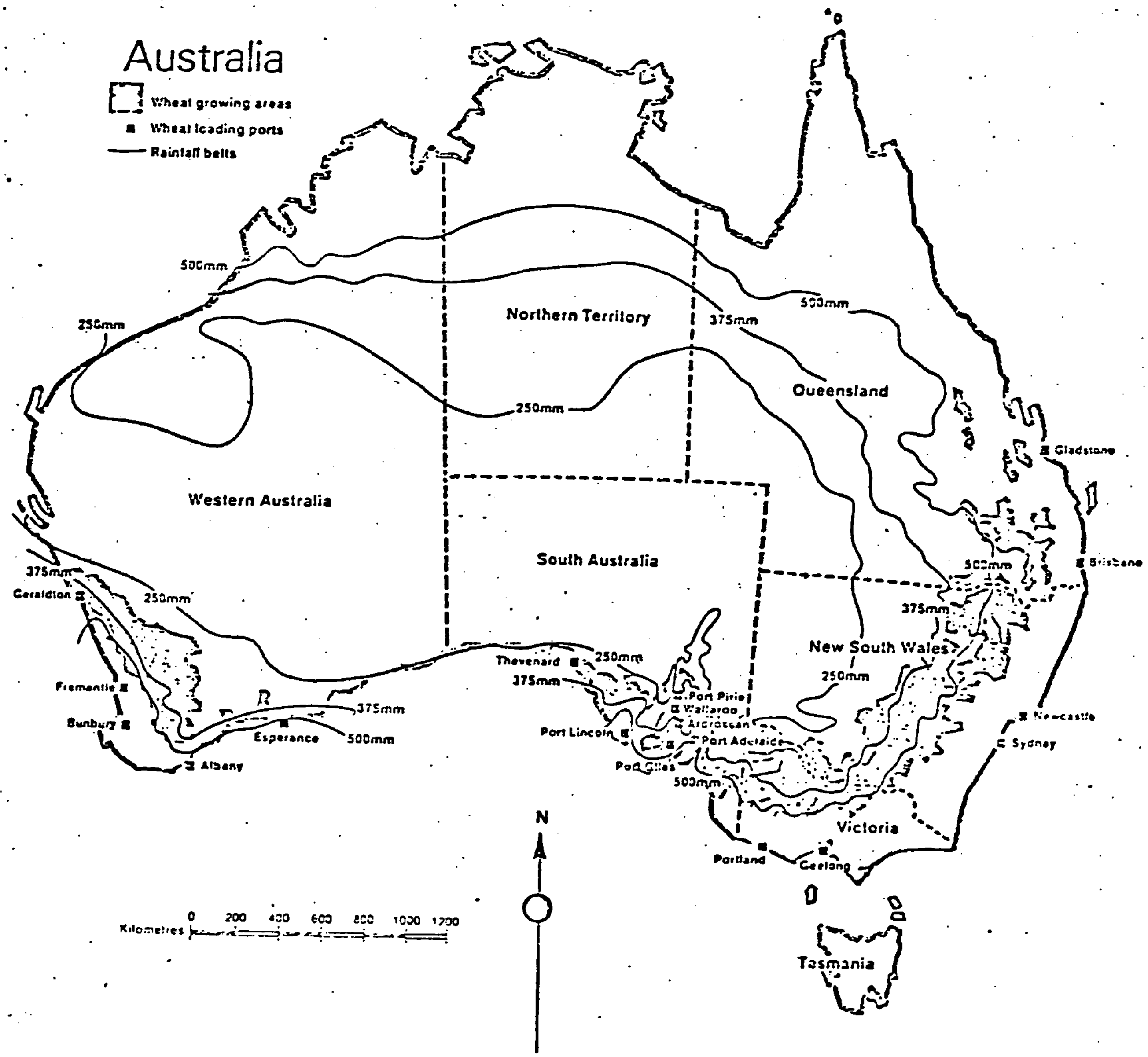
Australia
Wheat growing areas
Wheat loading ports
Rainfall belts
500mm
250mm
375mm
Northern Territory
Queensland
Western Australia
South Australia
New South Wales
Victoria
Tasmania
Gladstone
Brisbane
Newcastle
Sydney
Geraldton
Fremantle
Bunbury
Albany
Esperance
Thevenard
Port Pirie
Port Lincoln
Port Adelaide
Port Giles
Portland
Geelong
N
Kilometres
0
200
400
600
800
1000
1200

Figure 9

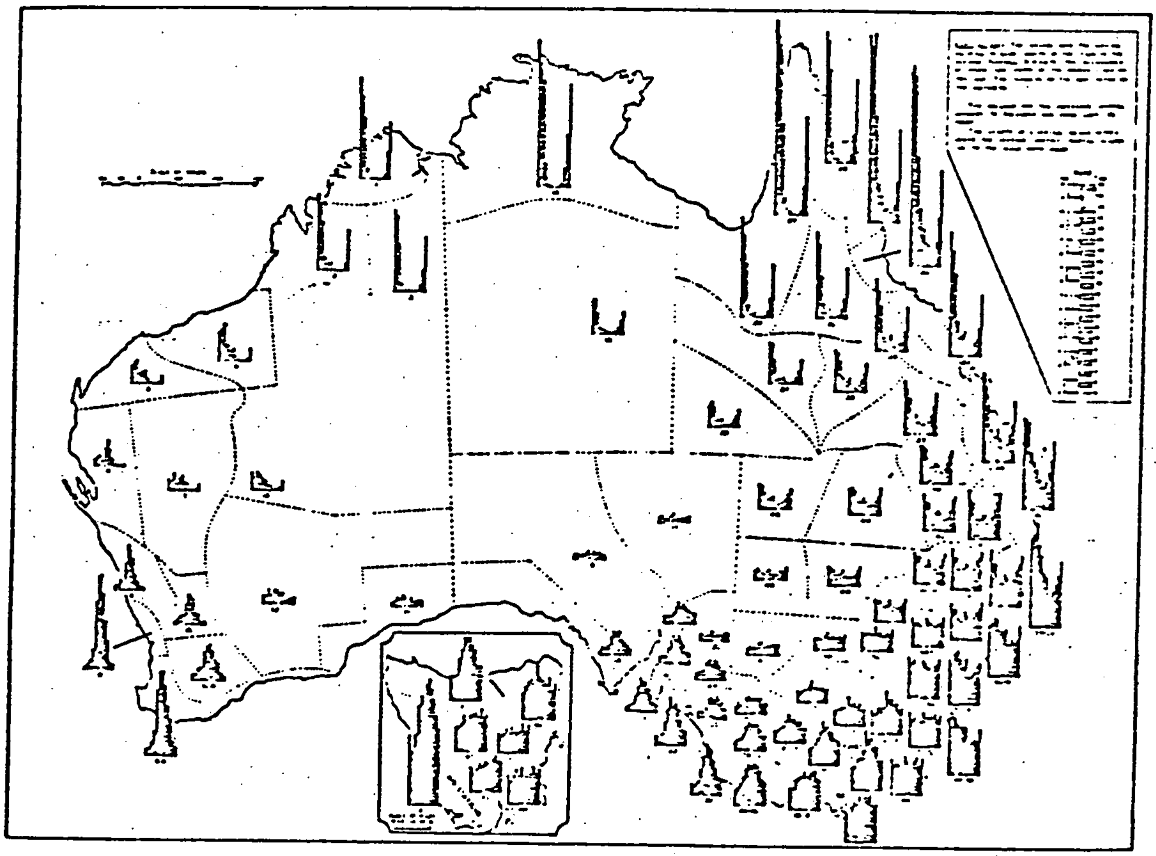

Figure 10. Monthly distribution of rainfall. The rainfall in each month of the year and for each district is shown by a black column; the months follow from left (January) to right (December) in each district diagram. The amount of rain for each month is shown by the height of the respective column, as from the scale on the right, in inches and cm. (From Bureau of Meteorology, 1962.)

and southern New South Wales, the climate is characterized as a Mediterranean type with maximum precipitation during winter (June, July, August). Dry weather during harvest time (summer) makes the climate ideal for winter-planted wheat. In northern New South Wales and Queensland, however, summer maximum precipitation dominates. These areas are consequently prone to hazards from thunderstorms and damp weather during harvest. Wheat growing is a much higher risk and weather damage from excessive rain has been high (Lovett, 1973). The pattern of rainfall distribution greatly affects the management of growing wheat such as in Queensland and northern New South Wales. In these areas, the land is fallowed for the summer and in some cases, for a longer period to conserve the limited moisture for the winter grown wheat. This practice, however, has also extended to other wheat growing areas of Australia with reasonably good success. The greatest variability of yield is found in New South Wales and Queensland. The lowest variability is found in Western Australia (see Table 5).

Wheat is subject to damage from low temperatures, particularly during the months of June, July, and August. Damage from frosts is more severe during a dry period. With favorable moisture, the wheat crop is able to withstand a succession of heavy frost with less damage (Foley, 1945).

Dry conditions that provide low preseason moisture can delay planting activities. This is a problem in northern New South Wales and Queensland where reserve soil moisture is very critical. In the southern states, e.g., Victoria, however, wet conditions during planting as well as during later growth stages can hamper yield with disease problems.

Wheat is Australia's main grain crop and accounts for 75 percent of the total grain area. Many farms are large and over half of them occupy

Table 5. Mean and Standard Deviation of Observed Wheat Yield in Australia (1940-1972)

State-Division	Yield (bushels/acre) Mean	Std. Dev.
New South Wales	16.3	6.1
Central Plains	12.6	6.7
North Central Plains	15.8	7.4
Northwest Slope	17.0	7.3
Central Slope	16.2	6.9
South Slope	16.6	7.7
Riverina	16.8	5.6
Queensland	19.2	6.0
Downs-Dalby (1960-72)	21.2	6.6
West Downs (1960-72)	17.3	6.6
South Australia	15.7	4.8
Central	18.9	4.8
Lower North	20.2	6.2
Murray Mallee	10.1	3.8
Southeastern	20.9	4.4
Upper North	16.5	6.6
Western	13.1	4.6
Victoria	18.4	5.8
Mallee	14.8	6.0
Northern	22.6	7.0
Wimmera	19.3	5.9
Western Australia	13.5	2.7

400 to 2500 hectares (1,000 to 6,000 acres). The main wheat, Triticum aestivum (common bread wheat) is grown. Most of the varieties are white-grained and have spring growth habits. However, they are sown in the fall or early winter (April to June) rather than the spring. Harvest is late spring or early summer (November to January).

Most of the wheat grown in Australia is soft, but areas in northern New South Wales and Queensland produce hard wheat. New South Wales is the major wheat producing state, followed by Western Australia, Victoria, South Australia and Queensland (Friend, et al., 1972).

Wheat is grown on six major soil types including the podzol, red-brown, solonized brown (Mallee soils), black, grey-brown and the lateritic sand-plain soils of Western Australia. More than half of Australia's wheat is grown on red-brown soils. The solonized brown soils are found in lower rainfall areas including Victoria and South Australia while the black fertile soils are found in Queensland and northern New South Wales and are characterized by its high water-holding capacity. The grey-brown soils are found principally in Victoria (Peterson, 1965).

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APPENDIX

Table A. Temperature Station Network for Wheat-Climate Analysis in Australia

Division, State	Name	Australian Meteo District No.	Latitude (S) Deg.	Latitude (S) Min.	Longitude (E) Deg.	Longitude (E) Min.
Central Slope, New South Wales	Coonabarabran	64008	31	18	149	18
	Conowindra	65006	33	36	148	42
	Dublo	65012	32	18	148	36
	Forbes	65016	33	24	148	00
	Molong	65023	33	06	148	54
	Parkes	65026	33	06	148	12
	Wellington	65034	32	36	149	00
Central Plains, New South Wales	Condobolin	50014	33	06	147	12
	Coonambk	51010	31	00	148	12
	Gilgandra	51018	31	42	148	42
	Nyngan	51039	31	36	147	12
	Quambone	51042	30	54	147	54
	Trangie	51048	32	00	148	00
North Central Plains, New South Wales	Morrel	53027	29	30	149	54
	Narrabri	53030	30	18	149	48
	Coonamble	51010	31	00	148	24
Northwest Slope, New South Wales	Bingara	54004	29	54	150	36
	Quirindi	55049	31	30	150	42
	Tamworth	55054	31	06	150	54
	Warialda	54029	29	30	150	36
Riverina, New South Wales	Deniliquin	74128	35	30	145	00
	Leeton	74069	34	33	146	24
	Mathoura	74062	35	51	144	54
	Moira	74076	36	00	144	54
	Urana	74110	35	18	146	18
	Wagga	74112	35	06	147	30
South Slope, New South Wales	Adelong	72000	35	18	148	00
	Brookfield	72009	35	48	147	54
	Birrinjuck	73007	35	00	148	36
	Cootamundra	73009	34	36	148	00
	Junee	73019	34	54	147	30
	Red Hill	72052	35	12	148	18
	Temora	73038	34	27	147	30
	Young P. O.	73056	34	18	148	18
Downs-Dalby Queensland	Dalby	41023	27	12	151	15
	Killarney	41056	28	12	152	11
	Stanthorpe	41095	28	39	151	54
	Toowoomba	41103	27	33	151	58
	Warwick	41111	28	14	152	02
	Cambooya	41011	27	43	151	52

Table A. (continued)

Division, State	Name	Australian Meteo District No.	Latitude (S) Deg.	Latitude (S) Min.	Longitude (E) Deg.	Longitude (E) Min.
West Downs, Queensland	Goondiwindi	41038	28	33	150	21
	Pittsworth	41082	27	43	151	38
	Wallangarra	41116	28	58	151	57
Western Australia	Bencubbin	10007	30	48	117	51
	Corrigin P. O.	10536	32	20	117	52
	Katanning	10579	32	42	117	33
	Kellerberrin	10073	31	38	117	43
	Merriden	10093	31	29	118	.17
	Muresk	10152	31	44	116	41
	Northam	10111	31	41	116	40
	Wandering	10648	32	40	116	41
	York P. O.	10144	31	53	116	45
Central, South Australia	Kadina	22006	33	58	137	43
	Maitland	22008	34	22	137	40
Lower North, South Australia	Clare	21014	33	50	138	37
	Georgetown P. O.	21020	33	21	138	24
	Kadina	22006	33	58	137	43
	Port Pirie	21043	33	11	128	01
	Snowtown	21046	33	47	128	13
Murray Mallee, South Australia	Lameroo P. O.	25509	35	21	140	31
	Penmark P. O.	24016	34	11	140	45
	Tailem Bend	24536	35	16	139	27
	Waikerie	24018	34	10	139	58
Southeastern, South Australia	Keith	25509	36	06	140	21
	Serviceton, Vic	78034	36	21	141	00
Upper North, South Australia	Port Augusta	19036	32	30	137	46
	Port Augusta P. S.	19066	32	33	137	47
	Port Pirie	21043	33	11	138	01
	Yongala	19062	33	02	138	45
Western, South Australia	Ceduna	18012	32	06	133	42
	Cleve	18014	32	42	136	30
	Cook	18110				
	Fowler's Bay	18030	31	59	132	27
	Kyancutta	18044	33	07	135	35
	Port Lincoln	18070	34	44	135	52
	Streaky Bay	18079	32	48	134	12
	Whyalla	18103	32	00	137	36

Table A. (continued)

Division, State	Name	Australian Meteo District No.	Latitude (S) Deg.	Latitude (S) Min.	Longitude (E) Deg.	Longitude (E) Min.
Mallee, Victoria	Beulah, P. O.	77004	35	54	142	24
	Birchip P. O.	77007	36	00	142	54
	Kerang	88023	35	42	143	54
	Lameroo, S. A.	25509	35	21	140	31
	Merbein	76026	34	10	142	04
	Mildura Aero.	76031	34	14	142	05
	Quyen	76047	35	06	142	18
	Rainbow	77035	35	54	142	00
	Swan Hill	77042	35	21	143	36
	Walpeup Res.	76064	35	06	142	00
Northern, Victoria	Avoca	81000	37	05	143	29
	Benalla	82002	36	30	146	00
	Bendigo	81003	36	46	144	17
	Boort	80002	36	06	143	42
	Charlton	80006	36	18	143	24
	Dookie	81013	36	18	145	42
	Echuca	80015	36	06	144	48
	Euroa	82016	36	42	145	36
	Kerang	80023	35	42	143	54
	Rochester	80049	36	21	144	42
	Shepparton	81044	36	24	145	24
	Wangaratta	82053	36	21	146	18
	Yarrawonga	81057	36	00	146	00
Wimmera, Victoria	Beulah P. O.	77004	35	54	142	24
	Donald	78011	36	24	143	00
	Jeparit	78015	36	06	142	00
	Horsham	79023	36	42	142	12
	Nhill	78031	36	18	141	39
	Serviceton	78034	36	21	141	00
	St. Arnaud Forestry	79040	36	36	143	18

NEW SOUTH WALES - AUSTRALIA

Variable	Deviation	Normal	Trend	May	Jun	Jul	Aug	Sep	Oct	Nov
Constant		1.000	6.27360	7.52951	8.77880	8.76730	9.02624	9.88573	13.24492	12.60481
Linear Trend, 1940-1950		11.000	0.44533	0.39878	0.29142	0.29986	0.22493	0.16114	-0.07395	-0.04154
Linear Trend, 1951-1976		26.000	0.08393	0.10593	0.16169	0.12340	0.13148	0.14810	0.11482	0.12665
Mar-May Z Index	DFN	0.000		0.02463	0.01908	0.02000	0.01707	0.00691	0.01265	0.01340
Mar-May Z Index	SDFN	0.000		-0.00010	-0.00008	-0.00007	-0.00008	-0.00005	-0.00008	-0.00009
Jun Z Index	DFN	0.000			0.04486					
Jun Z Index	SDFN	0.000			-0.00061					
Jun-Jul Z Index	DFN	0.000				0.03237				
Jun-Jul Z Index	SDFN	0.000				-0.00060				
Jun-Aug Z Index (WT)	DFN	0.000					0.04355			
Jun-Aug Z Index (WT)		0.000					-0.00022			
Aug Temperature		9.861						-0.36013	-0.35283	-0.65219
Jun-Sep Z Index (WT)	DFN	0.000						0.06535		
Jun-Sep Z Index (WT)	SDFN	0.000						-0.00103		
Oct Temperature		16.250							-0.44685	-0.55895
Jun-Oct Z Index (WT)	DFN	0.000							0.06698	
Jun-Oct Z Index (WT)	SDFN	0.000							-0.00128	
Jun-Nov Z Index (WT)	DFN	0.000								0.06397
Jun-Nov Z Index (WT)	SDFN	0.000								-0.00098
R Squared			0.19814	0.41419	0.51296	0.51718	0.51397	0.69275	0.88843	0.90876
Standard Error			3.70098	3.26069	3.07062	3.05729	3.06744	2.48056	1.52126	1.37566
Standard Variance			13.69727	10.63209	9.42872	9.34700	9.40921	6.15319	2.31423	1.89244

Standard Deviation of Yields = 4.01657

DFN = Departure from Normal
SDFN = Squared Departure from Normal
Yields Measured in Quintals per Hectare

Yields Based on 1940-1976
Meteorological Normals Based on 1940-1976

QUEENSLAND - AUSTRALIA

Variable	Deviation	Normal	Trend	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Constant		1.000	9.50909	10.22542	11.34063	12.81388	14.33936	13.21350	13.03703	11.91689
Linear Trend, 1940-1950		11.000	0.36123	0.36041	0.33418	0.10203	0.10310	0.10437	0.21284	0.31370
Mar-Jun Z Index	DFN	0.000		0.01340	0.01314	0.01472	0.01436	0.01646	0.01430	0.01707
Mar-Jun Z Index	SDFN	0.000		-0.00006	-0.00010	-0.00007	-0.00007	-0.00007	-0.00006	-0.00007
Jul Z Index	DFN	0.000			0.03989					
Jul Z Index	SDFN	0.000			-0.00016					
Jul-Aug Z Index (WT)		0.000				0.07758	0.06272	0.08166	0.08040	0.08578
Sep Temperature		14.484					1.41142	0.81984	1.43591	1.52147
Sep Z Index	DFN	0.000					0.01254			
Sep Z Index	SDFN	0.000					-0.00130			
Sep-Oct Z Index (WT)	DFN	0.000						0.00975	0.00726	0.00235
Sep-Oct Z Index (WT)	SDFN	0.000						-0.00024	-0.00021	0.00043
Nov Z Index	DFN	0.000							0.01148	-0.00368
Nov Z Index	SDFN	0.000							-0.00042	-0.00029
Dec Precipitation	DFN	95.645								0.04919
Dec Precipitation	SDFN	95.645								-0.00035
R Squared			0.07429	0.19952	0.31983	0.56966	0.69739	0.60158	0.65651	0.84470
Standard Error			3.92233	3.77107	3.60258	2.81392	2.49725	2.86541	2.77382	1.95194
Standard Variance			15.38465	14.22096	12.97858	7.91816	6.23627	8.21058	7.69410	3.81008

Standard Deviation = 4.01248

DFN = Departure from Normal
SDFN = Squared Departure from Normal
Yields Measured in Quintals per Hectare

Yields Based on 1940-1950
Meteorological Normals Based on 1940-1950

SOUTH AUSTRALIA - AUSTRALIA

Variable	Deviation	Normal	Trend	May	Jun	Jul	Aug	Sep	Oct	Nov
Constant		1.000	5.71564	6.62189	7.15707	7.44854	8.62831	8.25989	8.57782	8.81672
Linear Trend, 1940-1950		11.000	0.51560	0.41794	0.42397	0.42146	0.31910	0.31885	0.32522	0.32132
Mar-May Z Index		0.000		0.01977	0.01123	0.01146	0.01166	0.01014	0.01002	0.01115
Jun Temperature		11.548			-0.32012		-0.47745	-0.34293	-0.50645	-0.60702
Jun Z Index	DFN	0.000			0.03584	0.02837	0.02148	0.02193	0.01462	0.01555
Jun Z Index	SDFN	0.000			-0.00029	-0.00024	-0.00021	-0.00017	-0.00016	-0.00021
Jul Temperature		10.548					-0.18755	-0.30197	-0.41241	-0.55469
Jul Z Index	DFN	0.000				0.02172				
Jul Z Index	SDFN	0.000				-0.00025				
Jul-Aug Z Index (WT)	DFN	0.000					0.03543	0.01659	0.02046	0.01821
Jul-Aug Z Index (WT)	SDFN	0.000					-0.00067	-0.00035	-0.00070	-0.00079
Sep Z Index		0.000						0.02424		
Sep-Oct Z Index (WT)		0.000							0.03418	0.03652
Oct Temperature		16.161							0.36105	0.39496
Nov Precipitation		25.548								-0.03004
R Squared			0.23831	0.48854	0.64005	0.67872	0.76777	0.84251	0.86210	0.87124
Standard Error			2.83547	2.36190	2.08861	2.01082	1.77937	1.49683	1.43215	1.41644
Standard Variance			8.03988	5.57858	4.36231	4.04341	3.16616	2.24051	2.05107	2.00630

Standard Deviation = 3.19773

DFN = Departure from Normal
SDFN = Squared Departure from Normal
Yields Measured in Quintals per Hectare

Yields Based on 1940-1950
Meteorological Normals Based on 1940-1950

VICTORIA - AUSTRALIA

Variable	Deviation	Normal	Trend	May	Jul	Aug	Sep	Oct	Nov	Dec
Constant		1.000	4.49681	6.11389	6.33617	9.07296	8.38843	7.96071	8.09506	8.06449
Linear Trend, 1940-1950		11.000	0.84692	0.73554	0.75372	0.55171	0.60207	0.63600	0.62779	0.64067
Mar-May Z Index	DFN	0.000		0.01849	0.01523	0.01957	0.01528	0.01186	0.01017	0.01043
Mar-May Z Index	SDFN	0.000		-0.00006	-0.00006	-0.00007	-0.00007	-0.00005	-0.00004	-0.00006
Jun Z Index		0.000				-0.01045	-0.00530	-0.01120	-0.01366	-0.01788
Jul Z Index	DFN	0.000			0.04025	0.03572	0.02529	0.03212	0.02732	0.02805
Jul Z Index	SDFN	0.000			-0.00023	-0.00022	-0.00017	-0.00027	-0.00023	
Aug Temperature		9.806				0.69627	0.73838	0.60103	0.67654	0.51382
Aug Z Index	DFN	0.000				0.02966				
Aug Z Index	SDFN	0.000				-0.00051				
Aug-Sep Z Index (WT)	DFN	0.000					0.04611			
Aug-Sep Z Index (WT)	SDFN	0.000					-0.00057			
Sep Temperature		12.065					-0.47168	-1.01777	-0.96741	-0.76383
Aug-Oct Z Index (WT)	DFN	0.000						0.02877		
Aug-Oct Z Index (WT)	SDFN	0.000						-0.00044		
Aug-Nov Z Index (WT)	DFN	0.000							0.03553	0.03646
Aug-Nov Z Index (WT)	SDFN	0.000							-0.00057	-0.00072
Dec Precipitation		24.839								-0.02178
R Squared			0.42409	0.53832	0.66007	0.74849	0.85786	0.81644	0.83890	0.83849
Standard Error			3.03590	2.81036	2.49923	2.32920	1.79034	2.03454	1.90603	1.90843
Standard Variance			9.21671	7.89811	6.24614	5.42517	3.20533	4.13937	3.63296	3.64212

Standard Deviation = 3.93745

DFN = Departure from Normal
SDFN = Squared Departure from Normal
Yields Measured in Quintals per Hectare

Yields Based on 1940-1950
Meteorological Normals Based on 1940-1950

WESTERN AUSTRALIA - AUSTRALIA

Variable	Deviation	Normal	Trend	May	Jun	Jul	Aug	Sep	Oct	Nov
Constant		1.000	6.68886	6.83188	6.77199	6.73822	6.73867	6.85995	7.94851	7.92911
Linear Trend, 1940-1955		16.000	0.19275	0.18127	0.18506	0.19016	0.19031	0.17651	0.13376	0.14063
Feb-May Z Index		0.000		0.00338	0.00340	0.00455	0.00449	0.00166	0.00261	0.00253
Jun Z Index		0.000			-0.00401	-0.00456	-0.00472	-0.00289	-0.00735	-0.00740
Jul Temperature	DFN	10.452				0.55356	0.54843	0.32140	0.41341	0.54985
Jul Temperature	SDFN	10.452				-0.04412	-0.04734	-0.09090	-0.28162	-0.32212
Aug Z Index		0.000					0.00046	-0.00072	-0.00277	-0.00457
Sep Temperature		12.839						0.01938	-0.45838	-0.37952
Sep Z Index	DFN	0.000						0.02696		
Sep Z Index	SDFN	0.000						0.00008		
Oct Temperature		15.839							0.50761	0.49376
Sep-Oct Z Index (WT)	DFN	-0.000							0.03683	0.03896
Sep-Oct Z Index (WT)	SDFN	-0.000							-0.00032	-0.00033
Nov Precipitation		12.968								-0.02236
R Squared			0.28907	0.36141	0.37569	0.43725	0.43734	0.63442	0.75262	0.77040
Standard Error			1.53911	1.48280	1.49120	1.46727	1.49510	1.28133	1.07772	1.06270
Standard Variance			2.36885	2.19871	2.22368	2.15289	2.23534	1.64181	1.16148	1.12933

Standard Deviation = 1.79663

DFN = Departure from Normal
SDFN = Squared Departure from Normal
Yields Measured in Quintals per Hectare

Yields Based on 1940-1955
Meteorological Normals Based on 1940-1955

CENTER FOR CLIMATIC AND
ENVIRONMENTAL ASSESSMENT

Technical Note 76-3

An Index for Estimating Wheat Yield in Australia

Jerry D. Hill for

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