YIELD TRENDS IN THE WHEAT BELT OF SOUTH AUSTRALIA
DURING 1896-1941

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Summary

The history of the wheat industry in South Australia is reviewed to provide a background for discussion of the forms of trend observed in yield. The period chosen for examination was 1896-1941, and the analysis extends to practically the entire wheat belt, the basic territorial unit used for assessing yield being the hundred, the mean area of which in South Australia is approximately 118 square miles. As a preliminary to the evaluation of the trends it was necessary to estimate and to eliminate the effects of variations in seasonal rainfall; the statistical technique used was that of partial regression, and reasons are given for the choice of rainfall variates.

The major soil groups under cultivation are described and mapped.

The elimination of phosphorus as a limiting factor in yield coincided with the beginning of the period under review, so that in classifying the forms of trend observed it was convenient to divide the hundreds into two groups, according to whether they were opened for cultivation before or after the advent of superphosphate.

The nitrogen status of the major wheat soils is discussed, and after consideration of relevant literature, it is concluded that the nitrogen required by the crop has been drawn almost entirely from soil reserves under the exploitative systems of cropping generally employed. The wheat belt is broadly divisible into three parts:

1. Sandy, stony, and mixed mallee soils and related types in which nitrogen becomes limiting after 20-40 years of cropping, and yields subsequently decline owing to exhaustion of the reserves.

2. Loamy mallee soils and red brown earths, where yields increase over the period 1896-1941, but at diminishing rates as nitrogen becomes limiting.

3. Sandy and loamy mallee and transitional mallee-solonetz soils, where yield increases linearly throughout, mainly because exploitative cropping has not been in progress long enough to make its influence apparent. These regions constitute only a small proportion of the total area.

The economic restoration and maintenance of the nitrogen status of the wheat soils are discussed briefly.

I. HISTORICAL INTRODUCTION

Wheat-farming is the major industry of South Australia. One feature of its expansion to this predominant position is illustrated in Figure 1, which shows the annual acreage of the crop from 1836 to 1941; four clearly defined phases

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are apparent, and for the purpose of tracing the history of the industry it is convenient to use them with the following end points: 1836-85, 1886-1908, 1909-32, 1933-41. This partitioning is made primarily on the basis of acreage and its temporal rate of change, but at the same time carries other factors of importance in the development. Reference to the effects of these factors is made in the notes which follow.

(a) 1836-85

The production of wheat was first attempted on the mainland in 1838, and although only European varieties were available, fair success was achieved because of the relatively favourable climate in the immediate vicinity of Adelaide. Experience soon demonstrated the correct time to sow the crop, and the area rapidly expanded to the point where production exceeded local demand.

During the decade 1841-50, three advances gave a great impetus to production:

1. The invention of the stripper in 1843; this machinery considerably reduced the labour costs of harvesting, and made possible expansion into greater areas.

2. The construction of a flour mill in 1843 stimulated production of wheat for export of flour to interstate markets.

3. The abolition of the British corn duties in 1847 encouraged production to meet an export trade with Britain.

In the early years, cropping was confined to the Mt. Lofty Ranges and their slopes to the east and west, both on account of their geographical situation and

Fig. 1.—Annual acreage of wheat cultivated for grain in South Australia (1836-1941).
YIELD TRENDS IN THE WHEAT BELT OF S. AUSTRALIA 1896-1941

Fig. 2
Fig. 8
the readiness with which the arable parts could be brought into production. The combined effect of these factors is illustrated in Figure 2, which shows the distribution of the area under wheat in 1866, in relation to the isohyets of seasonal rainfall (total from April to November inclusive). Over practically all land thrown open for cultivation, the rainy season was followed by a long arid period extending throughout the summer, which precluded the use of rotation systems involving wheat that had been practised successfully in Europe. As a result, a new scheme was gradually developed, in which the land lay in fallow for periods of 9-12 months prior to sowing.

As the railway northward from Adelaide was extended, and subsidiary lines were constructed, expansion of the area followed, but cropping was still restricted mainly to regions with high rainfall. The distribution in 1875 is illustrated in Figure 3. It will be observed that this diagram shows the first signs of extension into areas with less than an average seasonal rainfall of 10 in.

Increasing demands of settlement next led to an attempt to convert large areas of mallee land to wheat-farming. The high costs and difficulties of clearing that were entailed would have retarded progress but for the invention, in 1876, of the multi-furrow stump-jump plough, followed later by the mallee roller. These two advances engendered a revolutionary change, by reducing costs and greatly facilitating the task of reclamation. Simultaneously with these developments, the railway network was carried further to the north, and considerable expansion followed in the most northerly counties. Figure 4 shows the distribution in 1884, and indicates clearly the extension in counties Blachford, Hanson, Newcastle, Granville, Frome, and Dalhousie, and the mallee districts of counties Daly and Fergusson, the area of crop sown in regions with a mean seasonal rainfall of less than 10 in. now assuming much larger proportions.

Toward the close of this period, two further, all-important, advances were made:

1. The selection, in 1881, of a variety known as Ward's Prolific, which was fairly resistant to rust, and yielded well under adverse conditions; it formed a base from which other selections were made, and constituted a major turning-point in varietal history.

2. During 1882-85, Custance demonstrated in the field at Roseworthy Agricultural College the value of superphosphate.

(b) 1886-1908

Throughout this interval, the total area remained approximately constant, but the distribution of the crop was altered radically. In the first 10 years further expansion occurred in the northern districts, on Eyre Peninsula, and in counties Burra, Eyre, Sturt, and Albert. These increases were compensated by a reduction in acreage on Yorke Peninsula and in regions of higher rainfall to the north of Adelaide. The distribution in 1896 is given by Richardson (1936). The closing years brought further changes. Much of the far northern section proved unsuitable because of the limited and erratic rainfall, and a marked recession followed,
MAP OF THE SOUTHERN PORTION OF SOUTH AUSTRALIA SHOWING DISTRIBUTION OF WHEAT FOR THE YEAR 1894.

NOTE: EACH DOT = 500 ACRES ISODYNALS FOR PERIOD APRIL - NOVEMBER INCLUSIVE.

Fig. 4
YIELD TRENDS IN THE WHEAT BELT OF S. AUSTRALIA 1896-1941

MAP OF THE SOUTHERN PORTION OF SOUTH AUSTRALIA SHOWING DISTRIBUTION OF WHEAT FOR THE YEAR 1908

NOTE. EACH DOT=500 ACRES ISOHYETS ARE FOR PERIOD APRIL-NOVEMBER INCLUSIVE

Fig. 5
the northern boundary being withdrawn except for isolated localities. At the same time further settlement occurred on Eyre Peninsula in the vicinity of ports, and cropping was again intensified on Yorke Peninsula and in counties Daly, Gawler, and Light. Figure 5, which gives the distribution in 1908, shows also the developments on mallee land near the River Murray in counties Albert and Alfred, and the extension in counties Buccleuch and Chandos following construction of a railway through the latter region.

Finally, from 1900 onward, mean yields increased, thus giving the first tangible results of Lowrie's* efforts to popularize the use of superphosphate.

(c) 1909-32

This period was marked by further withdrawals from the northern counties, but its outstanding feature is the second great surge of development, culminating in the peak of over 4 million acres during 1930-32 inclusive. This enormous expansion followed first from the extension of the railway system, during 1906-19, into the mallee areas of counties Albert and Alfred, and of Eyre Peninsula, and later from the stimulus given by the high prices offered for wheat, and repatriation policies following the 1914-18 war. The average distribution for the years 1924-5-6 is given by Richardson (loc. cit.), and that for 1930 in Figure 6.

Other important advances were a general adoption of the practice of applying superphosphate to the crop, the almost universal use of improved varieties that had been developed in the breeding programmes conducted in various parts of the Commonwealth, and the appearance of a close association between sheep- and wheat-farming.

(d) 1933-41

A complete reversal of the trend in acreage characterizes this short sequence of years, and by 1941 the total area in the State had fallen to just over 2½ million acres, the value attained about 1920. The rapidity with which this major readjustment occurred was due to the impact on the industry of the economic crisis of 1930 following immediately in the wake of four severe droughts during 1926-29. The balance was loaded most heavily against the wheat-growers of the marginal and submarginal regions, and comparison of the distribution in 1941 (Fig. 7) with that of 1930 demonstrates that by far the greater proportion of the reduction was made in the most recently settled tracts of mallee land. Actually, the exigencies of the economic situation only accelerated this reduction, for, as will appear, it was inevitable that the margin of cultivation would be withdrawn in these areas, just as it was in the most northerly parts after the expansive and optimistic settlement of the years 1880-96. This observation may even be extended. In the light of experience and from a consideration of the facts which have become available since 1941, it seems that additional large-scale adjustments should be made.

II. ORIGIN AND SCOPE OF THE INVESTIGATION

The problems associated with settlement of the marginal agricultural areas, which for a long time had been exercising the minds of governmental authorities.

* W. Lowrie succeeded J. D. Custance as Principal of Roseworthy Agricultural College.
YIELD TRENDS IN THE WHEAT BELT OF S. AUSTRALIA 1896-1941

MAP 01' T
PORTION
SHOWING DISTRIBUTION OF WHEAT FOR THE YEAR 1930.

NOTE. EACH DOT IS 500 ACRES.

PERIOD APRIL - NOVEMBER INCLUSIVE.

Fig. 6
MAP OF THE SOUTHERN PORTION OF SOUTH AUSTRALIA SHOWING DISTRIBUTION OF WHEAT FOR THE YEAR 1941

NOTE. EACH DOT REPRESENTS 500 ACRES. ISOLINES ARE FOR PERIOD APRIL–NOVEMBER INCLUSIVE.

Fig. 7
were brought suddenly into focus by the economic situation, and several enquirers were instituted to study the position of the wheat industry in South Australia. The Agricultural Settlement Committee (1931) reported to the Government on agricultural policy, settlement, and development, and discussed *inter alia* the expansion and disabilities of the industry, the problems of drought relief, and measures for increasing production. The marginal areas were subjected to a particularly close examination, and two papers by Perkins (1934, 1936) again gave them prominence. In the second paper, Perkins segregated the profitable from unprofitable wheat-growing areas, using as a criterion a minimum mean yield of 6 bushels per acre for the 20 years 1915-34 inclusive, and made further constructive suggestions for rehabilitating and stabilizing agriculture in the districts he had designated as unprofitable and unsuitable for the production of wheat as the major crop.

In 1934, the Commonwealth set up a Royal Commission to investigate the economic position of the industry for the whole country. The Commission's second report (1935) covered the wide range of problems confronting the industry, and submitted detailed information relating to costs of production in various districts.

Another step was taken locally in 1939. The Marginal Lands Committee (1939) was formed to consider again the situation as it pertained to South Australia. This Committee defined marginal lands as "areas which have been subdivided into blocks intended principally for wheat-growing and which have been utilized mainly for that purpose, but owing to the combination of an inadequate rainfall and unsuitable land have proved to be unsuitable for wheat as a major operation," and surveyed the wheat belt of the State to determine the areas within the ambit of the problem and the number of settlers involved. The Committee found that a primary cause of failure was the small size of holding, which prevented the grower from carrying sufficient sheep, and necessitated frequent cropping with wheat to maintain income. The solution suggested was to increase the size of holding so that more sheep could be carried, in association with a longer rotation such as fallow, wheat, oats, and pasture for two or more years according to soil type and rainfall, the length of the rotation being largely determined by the rapidity of deterioration of the pasture.

At the same time, an independent and more detailed examination of the available data by the author indicated that the yields in these regions were declining, and an investigation was begun to determine the trends, with the objectives of using them to delineate the areas concerned and for correlation with relevant concomitant observations. In 1940, the remainder of the wheat belt was included, so that all the advantages of contrast could be gained from a comparison with the trends of yield from districts favoured with a higher and more reliable rainfall, the 25-year period 1913-37 inclusive being chosen for examination since at that time it gave the longest standard sequence of yields over the most extensive range of soil types and climatic conditions. The results of this investigation were communicated privately to the Rural Reconstruction Commission in 1944.
Subsequently, when more precise information on the major soil types became available, the scope of the enquiry was widened further by extending the analysis to a longer series of records.

III. DATA AND ANALYTICAL METHOD

(a) Yield Data

The smallest territorial unit for which consecutive yield data are available is the hundred, the mean area of which in South Australia is approximately 76,000 acres, or 118 square miles. This unit was adopted, and the yields, expressed as mean yields in bushels per acre sown for grain, were extracted from the South Australian Statistical Register for all hundreds with an average area of not less than 1,000 acres under crop. The yields used in compiling the records are not estimates, but are derived from returns submitted by the growers. Errors in the figures quoted (mainly printing errors) were eliminated by checking the means against total production and acreage.

In all, some 296 hundreds have been examined, and their distribution among the regional divisions of the State as given by the Regional Planning Committee (1946), is as follows:

| Hundred | Yield
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuyts</td>
<td>48</td>
</tr>
<tr>
<td>Yorke</td>
<td>21</td>
</tr>
<tr>
<td>Pyap</td>
<td>19</td>
</tr>
<tr>
<td>Pinnaroo</td>
<td>24</td>
</tr>
<tr>
<td>Light</td>
<td>30</td>
</tr>
<tr>
<td>Sturt</td>
<td>12</td>
</tr>
<tr>
<td>Goyder</td>
<td>37</td>
</tr>
<tr>
<td>Tatiara</td>
<td>3</td>
</tr>
<tr>
<td>Flinders</td>
<td>42</td>
</tr>
<tr>
<td>Eyre</td>
<td>58</td>
</tr>
<tr>
<td>Fleurieu</td>
<td>1</td>
</tr>
<tr>
<td>Adelaide</td>
<td>1</td>
</tr>
</tbody>
</table>

In view of the possibility of future planning requirements, this method of reference was chosen rather than the older statistical subdivisions; an additional reason is provided by the fact that it has already been used in the report of the Pastoral and Marginal Agricultural Areas Inquiry Committee (1948). Figures 8 and 12 show the hundreds in relation to the regional boundaries.

In districts where cropping began prior to 1896, the analysis was confined to the period 1896-1941 inclusive, and where it commenced in 1896 or later only those hundreds which, by 1941, had a record of 20 years or more were selected. These limitations were imposed for three reasons:

1. All records of yield prior to 1896 are incomplete owing to the occurrence of two gaps, totalling 7 years, when no returns were taken, during 1885-88 and 1893-95, and sections of the records which exist do not give yields in sufficient detail for the purposes of the analysis.

2. In 1942, the Commonwealth Government, under war-time legislation, restricted the acreage to be sown to wheat.

3. The minimum of 20 years was chosen so that the trend in yield and the effects of seasonal rainfall could be accurately assessed.

(b) Rainfall Data

The finest subdivision of the year for which rainfall data are available in a form convenient for immediate use, is the calendar month. This unit was taken, and the data supplied by the Commonwealth Meteorological Bureau.
As so much was contingent upon making proper allowance for seasonal variations in yield, it was necessary to select the rainfall stations carefully. Owing to the circumstances that the area of each hundred is comparatively large, and that, in many instances, particularly those hundreds on the slopes of the Mt. Lofty and Flinders Ranges, there are considerable changes in altitude, the choice of rainfall stations would have been very difficult and of doubtful value, had recourse not been taken to two subsidiary sets of information:

1. A map showing the location of the area under crop in each hundred.
2. A map of isohyets of April-November rainfall.

On the whole, the rainfall records were remarkably complete, but there were, of course, the inevitable breaks in continuity. These were made good by substituting data from neighbouring stations, selected on the basis of the isohyets and the location of the crop. In the majority of hundreds, only one rainfall record was used, particularly in Nuyts, Eyre, Pyap, and Pinnaroo, where rainfall changes comparatively slowly with position; occasionally there were two, and more rarely three. In all, some 261 records were employed to eliminate the effects of seasonal rainfall.

(c) Analytical Method

In the examination of trends during the period 1913-37 the rainfall variates were determined by the following considerations.

(i) The Nature and Paucity of the Yield and Rainfall Data.—Since the yields in the greater proportion of hundreds were derived from very extensive areas, and the sequence was confined to a maximum of 25 years, these facts, coupled with the low density of rainfall stations and the enforced decision to employ monthly rainfall, precluded the possibility of making any detailed analysis of the rainfall. At the same time, however, it was recognized that some allowance would have to be made for the differential effects of rains in the several parts of the season.

(ii) The Average Distribution of Seasonal Rainfall.—Over the whole wheat belt the distribution of rainfall throughout the season is nearly symmetrical about a date in the interval mid-June to mid-July.

(iii) The Form of the Regression Function.—A previous analysis of yield data from Roseworthy College had shown that the regression of yield on rainfall, when expressed as a function of time, assumed the mathematically simple parabolic form, with a maximum in July. It was reasonable to assume that this form of relationship would be typical of most of the wheat-growing areas.*

(iv) The Period during which Rainfall is Effective.—It was shown by Trumble (1937) that the outer limits of the area at that time devoted to the cultivation of wheat corresponded roughly with the isochrone giving a season of five months' duration in which rainfall is effective, the average calendar interval being May-September. At the other extreme, the season ran to 7½ months in several isolated localities. The greatest proportion of the wheat belt, however, was situated in the zone between the 5- and

* This assumption will be substantiated in a paper in course of preparation.
7-month isochrones. In seeking a standard suitable over the whole wheat belt, April-November inclusive was chosen, as it gave a reasonable period prior to seeding in every district, and extended to harvest in all but a few places.

After taking account of these points, it appeared that the simplest adequate expressions which would effectively allow for variations in seasonal conditions would be the rains of the following subdivisions:

April and May
June, July, and August
September and October
November,

and these were taken as four rainfall variates.

Similar considerations apply in the analysis of the longer series of records, but the procedure has been modified by omitting November rainfall, since an exhaustive examination of the regressions of yield on this variate which had been obtained previously, showed that very little would be gained by its inclusion. With regard to the present investigation, the partial regressions on the remaining rainfall variates are by-products of the analysis, and their consideration has been relegated to another paper.

It is possible that rainfall of the preceding season and of the period December-March immediately prior to seeding, are correlated with yield, but such effects are also small when compared with those of the current season's rainfall to the end of October, and consequently they have been ignored. In any case, the crop records are not of sufficient length to account for them adequately.

At this juncture, it is important to mention two additional points. In the first place, only one meteorological element has been used to characterize the season, so that, in correlating it with yield, the regression obtained is the resultant of a number of components, one, the effect of the rainfall per se, and the remainder due to the direct and indirect effects of all other elements associated with the rainfall occurring in the several subdivisions under consideration. In the second place, it is obvious that definite optimal conditions must apply in various parts of the season, and the effects of the rainfall at all times are not strictly independent and additive. In the present enquiry, the quadratic terms, corresponding to such factors, have also been omitted, since in comparison with the linear terms they are of much less quantitative importance.

Four different functions of time have been employed to represent the temporal trends of yield. If \( y \) denotes yield, \( x_1, x_2, x_3 \) the rainfall variates in the order previously given, \( x_4 \) and \( x_5 \) time and its square, the four types of multiple regression were:

\[
Y = \bar{y} + b_1(x_1 - \bar{x}_1) + b_2(x_2 - \bar{x}_2) + b_3(x_3 - \bar{x}_3) + b_4(x_4 - \bar{x}_4) \ldots (1)
\]

\[
Y = \bar{y} + b_1(x_1 - \bar{x}_1) + b_2(x_2 - \bar{x}_2) + b_3(x_3 - \bar{x}_3) + b_4(x_4 - \bar{x}_4) + b_5(x_5 - \bar{x}_5) \ldots (2)
\]

\[
Y = b_1(x_1 - \bar{x}_1) + b_2(x_2 - \bar{x}_2) + b_3(x_3 - \bar{x}_3) + b_4x_4b_5 \ldots \ldots \ldots \ldots (3)
\]

\[
Y = b_1(x_1 - \bar{x}_1) + b_2(x_2 - \bar{x}_2) + b_3(x_3 - \bar{x}_3) + x_4/(b_4 + b_5x_4), \ldots (4)
\]

the bar over a symbol designating the arithmetic mean.
The coefficients were determined by the method of maximal likelihood (Fisher 1922), which, in the first two expressions, reduces directly to the standard technique of partial regression. In types (3) and (4) the logarithm of the likelihood is proportional to

\[ L = S(y - Y)^2, \]

where the summation is taken over the \( n \) observations in the sample, and the equations which must be satisfied on maximizing \( L \) for variations in the coefficients are

\[ \frac{\partial L}{\partial b_i} = 0, \quad i = 1, 2, \ldots, 5. \]

Since these equations are non-linear in the parameters, the ordinary procedure of least squares is not directly applicable, but the solution may be obtained by iteration, taking as a starting-point any conveniently calculable approximate values.

If \( b_i \) and \( b'_i \) denote the maximal likelihood estimate and its approximation respectively, and

\[ \hat{b}_i = b'_i + a_i, \]

the corrections to be applied are the solution of the equations

\[
\begin{align*}
\frac{\partial L}{\partial b_1} &= \frac{\partial L}{\partial b_1} + a_1 \frac{\partial^2 L}{\partial b_1 \partial b_1} + \ldots + a_5 \frac{\partial^2 L}{\partial b_1 \partial b_5} = 0 \\
\frac{\partial L}{\partial b_2} &= \frac{\partial L}{\partial b_2} + a_1 \frac{\partial^2 L}{\partial b_1 \partial b_2} + \ldots + a_5 \frac{\partial^2 L}{\partial b_2 \partial b_5} = 0 \\
\frac{\partial L}{\partial b_5} &= \frac{\partial L}{\partial b_5} + a_1 \frac{\partial^2 L}{\partial b_1 \partial b_5} + \ldots + a_5 \frac{\partial^2 L}{\partial b_5 \partial b_5} = 0
\end{align*}
\]

(5)

where in the set of derivatives on the extreme left, \( b_i \) is replaced by \( \hat{b}_i \) after differentiation, and in the remainder by \( b'_i \).

The solution is best obtained by inverting the matrix of second derivatives in equations (5), and if

\[ [c_{ij}] \]

\[ i, j = 1, 2, \ldots, 5 \]

denotes the inverse matrix, the \( a_i \) are given by

\[ a_i = \sum_j c_{ij} \left( - \frac{\partial L}{\partial b_i} \right) \]

\[ b_i = b'_i \]

\[ i, = 1, 2, \ldots, 5. \]

These corrections are added to the approximate values, and the whole process repeated if necessary.

The residual variance, \( s^2 \), is determined from the relation

\[ s^2 = \frac{1}{(n-5)} S(y - Y)^2 \]

since 5 adjustable parameters have been calculated from the data, and finally, the variance-covariance matrix of the \( \hat{b}_i \) is computed by multiplying the elements
of the inverse of the matrix
\[
\left( \begin{array}{c}
\frac{\partial^2 L}{\partial b_i \partial b_j} \\
\frac{\partial L}{\partial b_j}
\end{array} \right)_{b_i = \bar{b}_i, b_j = \bar{b}_j}
\]
i, j = 1, 2, \ldots, 5

by \( s^2 \).

The arithmetical detail of the process is illustrated with the calculations for the hundred of Crystal Brook, to the yields of which a multiple regression of type (3) was fitted. The steps in order are as follows:

1. Approximate values \( b'_1 \) (1.5208), \( b'_2 \) (2.0273), and \( b'_3 \) (0.6894) are found by fitting a multiple regression with \( x_1, x_2, x_3, \) and \( x_4 \) as independent variates, and the yields corrected for variations in seasonal rainfall.

2. Approximate values \( b'_4 \) (5.140) and \( b'_5 \) (0.2922) are then determined by taking the regression of \( \log \) (corrected yield) on \( \log \) (time).

3. After substituting these approximations, the numerical values of the elements in the matrix of coefficients and the quantities on the right-hand sides of equations (5) reduce to

\[
\begin{array}{ccccc}
76.09 & 11.27 & -1.34 & -2.33 & -88.21 \\
11.27 & 158.18 & 40.32 & -2.71 & -104.74 \\
-1.34 & 40.32 & 105.02 & 3.79 & 87.00 \\
-2.33 & -2.71 & 3.79 & 276.54 & 4482.12 \\
-88.21 & -104.74 & 87.00 & 4482.12 & 76774.51 \\
\end{array}
\]

and the inverse of the matrix of second order derivatives is

\[
\begin{array}{cccc}
13.40377 & -1.03221 & 0.52849 & -2.25917 \\
-1.03221 & 7.15029 & -2.78873 & -1.68294 \\
0.52849 & -2.78873 & 10.62995 & 1.45959 \\
-2.25917 & -1.68294 & 1.45959 & 68.17862 \\
0.14528 & 0.10998 & -0.10045 & -3.98684 \\
\end{array}
\]

each element being multiplied by \( 10^{-8} \).

The correction term \( a_1 \), for example, is then

\[
\{ (-13.40377 \times 10.2270) + (1.03221 \times 12.7233) - (0.52849 \times 18.3782) \\
- (2.25917 \times 26.1761) + (0.14528 \times 425.7731) \} \times 10^{-8} = -0.1309.
\]

The corrections and second approximations are

\[
\begin{array}{cccccc}
a_1 & a_2 & a_3 & a_4 & a_5 \\
-0.1309 & -0.0264 & -0.1698 & 0.1049 & -0.0006 \\
b_1 & b_2 & b_3 & b_4 & b_5 \\
1.3899 & 2.0009 & 0.5196 & 5.2449 & 0.2916 \\
\end{array}
\]
4. Repetition of the process using the second approximations gives the quantities

\[
\begin{array}{cccccc}
\frac{\partial^2 L}{\partial b_i \partial b_j} & \frac{\partial^2 L}{\partial b_1 \partial b_2} & \frac{\partial^2 L}{\partial b_3 \partial b_4} & \frac{\partial^2 L}{\partial b_5 \partial b_2} & \frac{\partial L}{\partial b_2} \\
76.09 & 11.27 & -1.34 & -2.32 & -89.01 & 0.0501 \\
11.27 & 158.18 & 40.32 & -2.64 & -105.67 & -0.0122 \\
-1.34 & 40.32 & 105.02 & 3.73 & 89.14 & 0.0062 \\
-2.28 & -2.64 & 3.73 & 270.40 & 4593.47 & 0.0804 \\
-89.01 & -105.67 & 89.14 & 4593.47 & 81049.55 & 1.4668 \\
\end{array}
\]

with inverse matrix

\[
\begin{array}{cccccc}
c_{ij} & 13.43794 & -1.00674 & 0.50627 & -3.31375 & 0.20244 \\
-1.00674 & 7.16927 & -2.80529 & -2.46979 & -0.13761 & -1.00674 \\
0.50627 & -2.80529 & 10.64437 & 2.14881 & 0.15257 & 0.50627 \\
-3.31375 & -2.46979 & 2.14881 & 100.43595 & -0.0018 & -3.31375 \\
0.20244 & -0.13761 & 0.15257 & -5.75168 & 0.34175 & 0.20244 \\
\end{array}
\times 10^{-8}
\]

yielding the following second corrections and third approximations:

\[
\begin{array}{cccccc}
a_1 & a_2 & a_3 & a_4 & a_5 \\
-0.0018 & -0.0012 & 0.0011 & 0.0495 & -0.0029 \\
\end{array}
\]

\[
\begin{array}{cccccc}
b_1 & b_2 & b_3 & b_4 & b_5 \\
1.3881 & 1.9997 & 0.5207 & 5.2944 & 0.2887 \\
\end{array}
\]  

At this point the working could have been terminated, as the solution is sufficiently accurate, but the calculations are here taken through a further stage, using the third approximations, to show that the third corrections are negligible. The numerical values are as follows:

\[
\begin{array}{cccccc}
\frac{\partial^2 L}{\partial b_i \partial b_j} & \frac{\partial^2 L}{\partial b_1 \partial b_2} & \frac{\partial^2 L}{\partial b_3 \partial b_4} & \frac{\partial^2 L}{\partial b_5 \partial b_2} & \frac{\partial L}{\partial b_2} \\
76.09 & 11.27 & -1.34 & -2.28 & -89.01 & 0.0501 \\
11.27 & 158.18 & 40.32 & -2.64 & -105.67 & -0.0122 \\
-1.34 & 40.32 & 105.02 & 3.73 & 89.14 & 0.0062 \\
-2.28 & -2.64 & 3.73 & 270.40 & 4593.47 & 0.0804 \\
-89.01 & -105.67 & 89.14 & 4593.47 & 81049.55 & 1.4668 \\
\end{array}
\]

\[
\begin{array}{cccccc}
c_{ij} & 13.43509 & -1.00801 & 0.50610 & -3.28818 & 0.19924 \\
-1.00801 & 7.16898 & -2.80602 & -2.47674 & -0.0804 & -1.00674 \\
0.50610 & -2.80602 & 10.64593 & 2.19272 & 0.0804 & 0.50627 \\
-3.28818 & -2.47674 & 2.19272 & 101.36102 & -0.0804 & -3.31375 \\
0.19924 & 0.0804 & -0.0804 & -5.75387 & 0.33901 & 0.0804 \\
\end{array}
\times 10^{-8} 
\]

\[
\begin{array}{cccccc}
a_1 & a_2 & a_3 & a_4 & a_5 \\
0.0007 & -0.0001 & 0.0001 & -0.0004 & 0.0000 \\
\end{array}
\]

\[
\begin{array}{cccccc}
b_1 & b_2 & b_3 & b_4 & b_5 \\
1.3888 & 1.9996 & 0.5208 & 5.2940 & 0.2887 \\
\end{array}
\]

5. Taking the values in (6) as the solution, the residual sum of squares is 275.07, with 41 degrees of freedom \((n = 46)\), giving a residual variance of 6.71,
from which the variances of the \( b_i \) are obtained by multiplying in turn by the diagonal elements of the matrix (7). The standard deviations and five values of \( t \) (Fisher 1946) in order are

<table>
<thead>
<tr>
<th>( t )</th>
<th>4.63</th>
<th>9.13</th>
<th>1.95</th>
<th>6.42</th>
<th>6.02</th>
</tr>
</thead>
</table>
| (41 degrees of freedom) so that \( b_3 \) is the only insignificant coefficient.  
After fitting the multiple regression (3), the sum of squares due to the regression formula can be very conveniently derived from the expression

\[
b_1 S y(x_1 - \bar{x}_1) + b_2 S y(x_2 - \bar{x}_2) + \ldots + b_p S y(x_p - \bar{x}_p) \]

but for regressions of type (4) the formula cannot be written so simply, and takes the form

\[
b_1^2 S(x_1 - \bar{x}_1)^2 + b_2^2 S(x_2 - \bar{x}_2)^2 + \ldots + b_p^2 S(x_p - \bar{x}_p)^2 + 2b_1b_2 S(x_1 - \bar{x}_1)(x_2 - \bar{x}_2) + \ldots + 2b_{p-1}b_p S(x_{p-1} - \bar{x}_{p-1})(x_p - \bar{x}_p) + 2b_1 \ldots b_p S(x_1 - \bar{x}_1)(x_2 - \bar{x}_2) \ldots (x_{p} - \bar{x}_p) \]

For all cases in which regressions of types (1) and (2) have been used, the multiple correlation coefficient has been determined, and hence the percentage of variance of yield, \( A \), ascribable to the average effects of the rainfall variates and time, from the relation

\[
A = 1 - \frac{(n-1)}{(n-p-1)} (1 - R^2) \quad . \quad . \quad . \quad (10)
\]

where \( R \) is the multiple correlation coefficient, \( n \) is the number of observations in the sample, and \( p \) the number of independent variates (Fisher 1924).

The sums of squares due to the regression formulae of types (3) and (4) contain the ordinary correction for the mean, \( \bar{y} \), and if this is deducted from both sums an index of multiple correlation may be defined, by analogy with the multiple correlation coefficient, as the ratio

\[
R^2 = \frac{S Y^2 - 2S y Y - \bar{y}^2}{S(y - \bar{y})^2} \quad . \quad . \quad . \quad (11)
\]

and the percentage of variance, corrected for positive bias in \( R^2 \), will be correspondingly

\[
A = 1 - \frac{(n-1)}{(n-p-1)} (1 - R^2), \quad . \quad . \quad . \quad (12)
\]

\( p \) now designating the number of coefficients in the regression formula after deducting one for the mean. \( R \), and \( A \), have been determined for all hundreds in which they are appropriate.

IV. Soil Groups of the Wheat Belt

The geographical distribution of the soil groups in relation to the isohyets of seasonal rainfall and the boundaries of the hundreds, is illustrated in Figure 8. This map summarizes the best information available at the present time. It must be realized that the allocations have been made on a rather broad basis; within the boundaries as mapped, variations of type exist owing to geological
Fig. 8. Major Soils Zones in the Wheat Belt of South Australia (drawn
Drawn from data supplied by the Division of Soils, C. S. I. R., and R. I. Herriot.)
and climatic differentiation, and consequently, if the grouping is applied in fine
detail it is liable to be misleading.

The descriptions of the soil groups are as follows:

(i) **Podsols.**—These are leached soils with a grey surface and generally a
yellow or mottled clay subsoil. The surface soil is commonly of light texture,
and acid in reaction; lime is absent from the profile except where the soil is
residual on lime-bearing rocks, and even under these conditions it occurs only
in the lowest horizon. The group as mapped includes the lateritic podsols of
Kangaroo Island, the Mt. Lofty Ranges, and southern Eyre Peninsula, where
ironstone gravel or massive laterite appears in the profile at or near the surface,
Fertility of the podsols is low to moderate, but generally enhanced by humid
climatic conditions.

(ii) **Red Brown Earths.**—This group has brown surface soils usually loamy in
texture with red or red-brown structured clay subsoils. The surface is neutral
to slightly acid in reaction, and lime occurs in the deeper subsoil. These are the
most fertile of the soils used extensively for wheat-growing in South Australia,
and are favoured by a fairly reliable winter rainfall. In the zone as mapped,
there are very restricted occurrences of black earth or chernozem soils, the
principal one being at Saddleworth.

(iii) **Desert Loams.**—In these brown soils of the arid areas there is usually
a light to moderately heavy surface horizon over a clay subsoil in which occurs
an accumulation of lime, and frequently, visible gypsum. The profile is alkaline
throughout. The fertility of this group is very low and the various types erode
rapidly under cultivation.

As mapped, the group includes:
1. The desert loams, which constitute the major portion of Flinders.
2. The types occurring at the western extremity of the wheat belt in the
   vicinity of Fowler’s Bay. These are grey-brown loamy soils of varying
   depth which possess a high salinity at or near the surface in many parts,
   and have affinities to the desert loams.
3. The loamy mallee soils extending in an arc from Kimba to Cowell. These
   soils occur in a region of low rainfall, and hence are agriculturally similar
to the desert loams and have accordingly been included with them.

Both the regions of the true desert loams and red brown earths are
characterized by a high proportion of skeletal soils on the hills and ranges, too
stony and shallow for cultivation.

(iv) **Rendzinas.**—Black soils, occasionally degraded to grey or grey-brown
by saline conditions or leaching, lying residual on soft and/or clayey calcareous
parent material. The surface is neutral to slightly alkaline in reaction. The soils
are irregular in depth, of variable fertility, and occur over a moderately wide
range of climatic conditions.

(v) **Solonized Soils.**—Soils of this type constitute the largest single group
in the agricultural regions of South Australia. They are brown in colour and
have been solonized. A prominent morphological feature is the large accession
of calcium carbonate which was probably wind-borne.

The main group includes a subgroup originally described as mallee soils, and it is proposed to use this term here, since all occurrences in the wheat belt of the State carry the characteristic mallee vegetation associations (Wood 1937).

Texture is variable, and reaction alkaline. Different regions are dominated by (1) loamy soils; (2) stony soils where the development, exposure, and disintegration of a travertine limestone pan have resulted in a stony surface soil; (3) sandy soils, some of which have arisen by the accumulation of siliceous sands, stripped by aeolian action from the leached surface horizons of adjacent stony areas. Where all three or any two of these types occur together with no one predominant, the soils have been classed and mapped as mixed mallee.

A related class, described by the term calcareous aeolianite, has also been included in this group. These soils are consolidated calcareous sands which have not been solonized but in their original state carried mallee (Eucalyptus oleosa) interspersed with open spear grass (Stipa spp.) plains.

(vi) Solonetz Soils.—Former concentrations of salt have affected the profiles of these soils but they now contain relatively small amounts. The subsoil contains a marked proportion of exchangeable sodium. The soils are generally of light texture, particularly in the surface horizon, and in South Australia have developed on modified sand-ridge country. They are neutral to alkaline in the surface, and alkaline in the subsoil, and occur over a moderately wide range of climatic conditions. Fertility varies according to the character of the precursor soil and the stage of solonization, but is principally low.

(vii) Transitional Mallee-Solonetz Soils.—In the zone between the recognized brown solonized and solonetz soils, there occurs a substantial area featuring the characteristic mallee physiographic pattern of alternating dunes and flats, the former being solonetz, and the latter typical brown solonized soils; the proportion of solonetz to solonized soil increases on any line approaching the solonetz region. The rainfall of these areas is generally higher than that of the mallee, and cropping is confined mainly to the interdunal spaces.

(viii) Wimmera Grey Soils.—The profile, which is alkaline and may be partly solonized, is uniformly heavy, consisting of grey or brown clays, becoming mottled with depth; the grey clays may have a self-mulching surface. Lime and gypsum occur to some degree in the subsoil. The South Australian occurrence of this type is a small intrusion at the western extremity of the fertile soils of the Victorian Wimmera.

V. SUMMARY OF RESULTS AND DISCUSSION

(a) Accuracy of the Regression Formulae

The complete tabulation of the results of this investigation has not been included, since it is too extensive for reproduction herein. Copies have, however been filed, and are available for inspection.*

*At the libraries of the Council for Scientific and Industrial Research, 314 Albert Street East Melbourne, and its Section of Mathematical Statistics, University of Adelaide.
The statistical significance, with minimum odds of 19:1, has been established for the trends in yield of practically all hundreds except those which have been classified as type III of Figure 11 (*vide infra*), and by appropriately combining the probabilities of both significant and insignificant coefficients, any doubts regarding the few exceptions are removed. Such tests are, however, really not required, since the close similarity of form in the trends of contiguous hundreds provides sufficient proof.

Table 1 sets out the distribution of the coefficients and indices of multiple correlation within arbitrary, but convenient, subdivisions of the range of seasonal rainfall (total of April-November inclusive) and the mean values of the percentage variance, the value 83 per cent., for example, being the mean of the 14 cases in which the coefficient or index was $\geq 0.91$. In 267 hundreds, 50 per cent. or more of the observed variation in yield is expressible in terms of the four types of function employed in the analysis.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>&lt; 8</th>
<th>8-10</th>
<th>10-12</th>
<th>12-14</th>
<th>14-16</th>
<th>16-18</th>
<th>&gt; 18</th>
<th>Total</th>
<th>Per Cent. Variance (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 0.91$</td>
<td>7</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>14</td>
<td>83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.81-0.90</td>
<td>39</td>
<td>54</td>
<td>44</td>
<td>29</td>
<td>3</td>
<td>169</td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.71-0.80</td>
<td>9</td>
<td>34</td>
<td>19</td>
<td>9</td>
<td>3</td>
<td>1</td>
<td>84</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>0.61-0.70</td>
<td>3</td>
<td>12</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>21</td>
<td>37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.51-0.60</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>6</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.41-0.50</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>55</td>
<td>95</td>
<td>78</td>
<td>49</td>
<td>13</td>
<td>5</td>
<td>1</td>
<td>296</td>
<td></td>
</tr>
</tbody>
</table>

The relation which exists between the measures of correlation and seasonal rainfall reflects largely the strength of the relation between yield and rainfall, since, in the majority of hundreds, the regression of yield on time is the smaller contributor to the total variation ascribable to the regression formula. Considering the results as a whole, it can be claimed that a rainfall record provides a sufficiently accurate index of seasonal conditions in this environment.

Table 2 lists the distribution of the correlations within the several soil types of the wheat belt. As rainfall and soil type are, to some extent, related, these distributions are not completely independent of that in Table 1, but, nevertheless, they do indicate that the claim made above holds also on all principal soils. The grand total of 385 does not agree with that of Table 1 because 39 hundreds, comprised equally of two soil types, have been included under both in preparing the table.

(b) The Types of Trend Which Occur

Before proceeding further with the discussion, it will be helpful to amplify certain points mentioned in Section I, and introduce others, so that each individual sequence of yields can be viewed in its proper relation to the full
cropping history of the corresponding district. With this objective, it is convenient to divide the hundreds into two categories: (i) those in which cropping began prior to 1896; and (ii) those in which cropping began during or after 1896.

**Table 2**

**Distribution of Coefficients and Indices of Multiple Correlation Within Soil Types**

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Mallee Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation</td>
<td>Sandy</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>$\geq 0.91$</td>
<td>2</td>
</tr>
<tr>
<td>0.81-0.90</td>
<td>39</td>
</tr>
<tr>
<td>0.71-0.80</td>
<td>16</td>
</tr>
<tr>
<td>0.61-0.70</td>
<td>2</td>
</tr>
<tr>
<td>0.51-0.60</td>
<td>1</td>
</tr>
<tr>
<td>0.41-0.50</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>59</td>
</tr>
</tbody>
</table>

(1) **Hundreds in which Cropping Began prior to 1896.**—By 1896, districts in this class had records of yield varying up to 50 years in length, the duration of record being fairly strongly and positively correlated with seasonal rainfall. Since the land was virgin, yields obtained at the outset were reasonably high, and in some localities were probably maintained for varying short periods. Three principal systems of cropping came into use, which, in order of appearance, were wheat continuously, fallow-wheat, and fallow-wheat-oats, and no returns were made to the soil other than what was introduced in the fallows. These methods inevitably led to depletion of essential chemical elements, and, with phosphorus in particular, to almost complete exhaustion of soil reserves. With the consequent reduction of fertility, yields began declining at rates varying from district to district, depending upon initial fertility, date of settlement, rainfall, intensity of cropping, and other subsidiary factors, of which wind and water erosion were probably the most important. The available evidence indicates that during the last ten years of the century yields in practically all districts had reached a very low level.

During 1896-1910, the use of superphosphate had spread widely, and as is well known, there was an immediate and marked response in yield. The great changes in acreage on Yorke Peninsula and in counties Gawler, Light, and Daly between 1884 and 1908 are, in part, a reflection of these facts.† There seems little doubt that the area of wheat was reduced because yields had fallen to such

† Richardson’s illustration of the distribution in 1896 reveals a very considerable reduction in the area of wheat for these parts of the State.

* Wimmera grey loam included with red brown earth.
Fig. 12. Distribution of Yield Trends in [Region Description]
in the Wheat Belt of South Australia.
a low level under the intense cropping (vide Figs. 3 and 4) of previous years: the response to superphosphate provided the stimulus for the re-intensification of cropping. But, apart from the increase in the phosphorus status of the soils, the advances made by the introduction of improved varieties and the closer association of sheep- and wheat-farming, the factors that had previously been responsible for the decline in yield were still operating, with the result that the rate of improvement was not generally maintained. In Figure 9, the courses of

![Graph](image)

**Fig. 9.—Reconstruction of the entire course of yield in four districts opened prior to 1896.**

yield in four hundreds have been reconstructed, after making allowances for variations in seasonal rainfall, to illustrate some of these points. The following notes on each district are relevant:

<table>
<thead>
<tr>
<th>District</th>
<th>Soil Type</th>
<th>Rainfall</th>
<th>Cropping Commenced</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Red brown earth</td>
<td>14-16 in.</td>
<td>1850-1855</td>
</tr>
<tr>
<td>(2)</td>
<td>Red brown earth and</td>
<td>14-16 in.</td>
<td>1860-1865</td>
</tr>
<tr>
<td></td>
<td>loamy mallee</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3)</td>
<td>Loamy mallee</td>
<td>12-14 in.</td>
<td>1880 (exact)</td>
</tr>
<tr>
<td>(4)</td>
<td>Mixed mallee</td>
<td>10-12 in.</td>
<td>1878 (exact)</td>
</tr>
</tbody>
</table>

The declines prior to 1896 are represented as linear functions of time, but it is probable that if complete data had been available they would have been found to be exponential. The differences between districts (1) and (2) during 1860-96 are consistent with the fact that the first possessed the more fertile soil, which had been cropped for some ten years longer. Districts (3) and (4) also fall appropriately into sequence according to their rainfall and the natural fertility of the soils. Their initial yields are considerably lower than, and the rates of decline exceed, those of (1) and (2).

After 1896, the response to superphosphate and other factors tending to increase yield, is manifest in the four curves, but their forms vary according to the general conditions in each area. A high rate of increase is present for varying short periods immediately after 1896 in all hundreds opened for settlement before that date, but has only been definitely established for curves similar to that of district (1) and one other type. In such cases the period of cropping before 1896 was generally long and intense. A second important factor which also partly accounts for the difference between districts (1) and (2) is that in the latter
there has been a rapid increase during recent years in the number of stock, mainly sheep, associated with wheat-farming, accompanied by a lengthening of rotations, whereas in the former the general tendency has been to maintain the system based on short-term rotations.

District (4) demonstrates clearly the inability of these particular soils to withstand frequent cropping, since yield eventually declines again notwithstanding the advancements made in the past 40 years.

The six principal types of trend which occur are illustrated in Figure 10.

Fig. 10.—The principal types of yield trend in hundreds opened before 1896.

Types I and VI represent the extremes of the range, and there is a gradual transition from type to type within it.

(ii) *Hundreds in which Cropping Began during or after 1896.*—In this category, settlement coincided with the introduction of superphosphate, or occurred at a later date. The hundreds concerned are scattered over a wide range of soil and season, but the bulk of the group is located in the mallee areas of Nuyts, Eyre, Pinnaroo, and Pyap. In these regions, cropping methods in the early stages are exploitative through circumstances incidental to pioneering on land carrying mallee vegetation. Mallee stumps remaining in the ground after the first clearing repeatedly send out new growth, and the settler crops continuously for some years, burning the stubbles to destroy the shoots. The situation is also made more acute since the growers have only limited capital and credit resources, and this provides an additional reason for adopting such methods in an endeavour to improve the income of the first few years. During
this phase, which takes on the average about five years to complete, the principal factor limiting yield, apart from rainfall, is probably a deficiency of available nitrogen. In the course of time, however, as fallowing and other measures for increasing production are introduced, yields would be expected to improve, but the subsequent course would vary according to soil, rainfall, and the practices adopted. The types which occur are illustrated in Figure 11. The range is not as great as that of Figure 10, since the situation is not complicated by the effects of cropping prior to the advent of superphosphate. Type III applies to hundreds which have only been settled recently, the records being so short that the position with respect to trend is still indeterminate. The positive regressions on time are all statistically insignificant, and from this restricted point of view the sequences of yields are in accord with the hypothesis that the trends are zero, but consideration of all relevant information indicates clearly that hundreds classed in this group are repeating, some 10-20 years later, the first stage of either curve I or curve II. In this sense, the type III curve may be regarded as a subtype of I or II. Included in this group also are several cases in which the trend is practically zero. Hundreds with trends of type IV are easily distinguished, since they are almost entirely confined to two soil classes, and the regressions are strongly significant and of much greater magnitude than those of type III.

In general, both sequences of types are intimately related to improvement in the class of soil and in particular are arranged in order of increasing abundance of nitrogen; this point is elaborated further at various stages below in this section.

(c) *Survey of the Trends and Their Distribution*

Figure 12 depicts the geographical distribution of the trends. Diagrammatic representation has been simplified by assigning a specified type of trend to the whole of each hundred to avoid the complication that would inevitably ensue on a map of this scale if the actual location of the crop were given in each. Throughout the remainder of this section, frequent reference will be made to the curves of Figures 10 and 11, and to save repetition they will be quoted as, for example, I(10), III(11).
# INDEX OF HUNDREDs

<table>
<thead>
<tr>
<th>Names</th>
<th>Eyre (cont.)</th>
<th>Flinders (cont.)</th>
<th>Goyder (cont.)</th>
<th>Pyp (cont.)</th>
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<tr>
<td>Miller</td>
<td>64. Moseley</td>
<td>126. Coonatto</td>
<td>185. Clare</td>
<td>243. Brownlow</td>
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<td>26. Carawa</td>
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<td>209. Light</td>
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<td>32. Walupppie</td>
<td>95. Moody</td>
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<td>214. Moorooroo</td>
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<td>34. Finlayson</td>
<td>97. Dixon</td>
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<td>216. Ettick</td>
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<td>35. Tarlton</td>
<td>98. Ulipa</td>
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<td>217. Port Germein</td>
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<td>37. Kaloonera</td>
<td>100. Stokes</td>
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<td>219. Light</td>
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<td>40. Chandada</td>
<td>103. Mortlock</td>
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<td>222. Belvidere</td>
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<td>41. Karculaby</td>
<td>104. Koppio</td>
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<td>223. Dutton</td>
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<td>105. Hutchison</td>
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<td>224. Moorooroo</td>
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<td>112. Wyacca</td>
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<td>240. Pooginook</td>
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<td>242. Murtho</td>
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<td>125. Willochra</td>
<td></td>
<td>244. Striling</td>
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</tr>
<tr>
<td>63. Coultney</td>
<td></td>
<td></td>
<td>245. Wirrega</td>
<td></td>
</tr>
</tbody>
</table>

*Names of regions are printed in italics.*
In surveying the whole wheat belt, reference to both maps is greatly facilitated by using a *primary* subdivision into the somewhat artificial* regions of the Regional Planning Committee (loc. cit.), rather than a natural one based on soil type and rainfall. The year or period during which settlement took place is listed with each group of hundreds.

**Nuyts**

1. Grey-brown loamy soils with affinities to the desert loams; rainfall approximately 10 in. throughout the group.
   
   Generally speaking, the soils improve along the line from Fowler’s Bay to a point just east of Penong.
   
   a. Miller (1)†, Wookata (2), Sturdee (3), and Caldwell (4) (1896).—Although these hundreds were opened in 1896, analysis of the data could only be made from 1907, since all records prior to this date were included as one in the returns. During the first eleven years, yields may have increased slightly, but it is much more likely that they were only maintained. The curves show a steady decline from 1907, which is not typical of the group, possibly owing to a higher level of salinity in the soils and the fact that the areas under cultivation are too small to be representative. For convenience in mapping, they have been included as I(11). Figure 13 illustrates the smoothed trend in Wookata after variations due to seasonal rainfall have been eliminated, or as may be alternatively viewed, the course that yield would have followed if the rainfall variates had remained constant at their average values, throughout the period under examination.
   
   b. Nash (5), Magarey (6), Giles (7), Cohen (8), Burgoyne (9), Bagster (10), Kevin (11), Keith (12), Catt (13), Horn (14), and Bartlett (15) (1890-1900).—For some 15-20 years yields slowly increased, but under the severe conditions this effect was transitory, and they subsequently declined, following courses I and II(11), according to local conditions. The curve for Burgoyne is also given in Figure 13. The influence of the slight improvement in the class of soil is shown by the sequence Wookata, Nash (the type I curve of Fig. 11), and Burgoyne.

2. Calcareous aeolianite; rainfall 9-10 in.
   
   a. O’Loughlin (16), Moule (17), Goode (18), Bonython (19), Wandana (20), Chillundie (21), Guthrie (22), Blacker (23), Wallanippie (24), Carawa

* i.e. Artificial for present purposes.
† The numbers in brackets refer to the numbered hundreds on the maps (Figs. 8 and 12).
with traditional being an exception. Scott (38), and Murray (39) (1896).—The last three hundreds lie in the transitional zone between the calcareous sands and the adjoining stony mallee region; their trends resemble the remainder of the group, and consequently they have been included here. All yields show the expected increase, but as with the previous group, the effect is temporary, and they subsequently decline, the types being I and II (11) according to local conditions. The type II curve of Figure 11 is actually that of Perlubie. Carawa, with its type IV (11) curve, stands out as an exception. In this hundred, seasonal conditions are much better than indicated by the 10 in. isohyet because in the small section to which cropping has been restricted the rainfall is, on the average, nearly 11½ in. The maximum yield, attained in 1941, was, however, only about 7 bushels per acre.

b. Petina (27), Hague (25), Walpuppie (32), Cungena (36), and Wallala (28) (1907-17).—In these hundreds the records are too short to make a definite decision regarding trend, but the yields show small increases, and this observation agrees with the view that the subgroup is following, some 10-20 years later, the first phase of the course set by the older districts on this class of soil. The trends have been classified as type III (11).

Hague, which was opened in 1911, declines from the outset; only a small area is cultivated, and it has probably been exploited fully. In Figure 12 this hundred has been included under type I (11). Figure 14 shows the courses of yield in Carawa and Cungena.

![Fig. 15](image1.png) ![Fig. 16](image2.png)

3. Stony mallee; rainfall 10-13 in.

This group is mapped as stony mallee, but practically all the wheat is grown on scattered areas of sandy mallee which was derived from granitic parent rock.

a. Forrest (43), Wrenfordsley (46), Rounsevell (47), Witera (48), Campbell (44), and Wright (49) (1889-96).—With such a short period of light cropping prior to the advent of superphosphate, fertility was barely affected in these hundreds, and consequently no marked reaction occurs immediately after 1896. Yields steadily increase up to 1941, and all have been classified as type IV (11). These observations, coupled with the higher mean yields, provide a striking contrast with those made previously, and are directly ascribable to the more fertile class of soil and the additional 2-3 in. of seasonal rainfall. Figure 15 shows the course of yield in Rounsevell.

b. Travers (56) and Wallis (57) (from Eyre), Chandada (40), and Inkster (45) (1910-17).—Trends have not been definitely established, but the results
obtained agree generally with the remainder of the group. They have been classified as type III(11).

Eyre

1. Sandy mallee; rainfall 9-11 in.

All hundreds were opened for settlement during 1914-19, and are divisible into two subgroups, depending on the nature of the soils.

a. Koolgara (29), Yantanabie (33), Kaldoonera (37), Karcultaby (41) (from Nuyts), Condada (50), Carina (51), Palabie (58), Wannamana (59), Mamblin (60), Kappakoola (61), and Warramboo (62).—The trends are in accordance with the expectation that yields will improve for some years, but owing to the short cropping history only three have been definitely established, namely, Wannamana, Kappakoola, and Warramboo. It will be noted that the latter two hundreds lie in close proximity to the 11 in. isohyet. This trio has been classified as type IV(11), and the remainder as type III(11).

b. Minnipa (52), Yaninee (53), Pygery (54), and Wudinna (55).—The distinguishing feature of the soils in these hundreds is their granitic origin, and the greater fertility is reflected immediately in the higher mean yields, which are similar to those of Rousevell etc. The trends of Yaninee and Pygery have been established as type IV(11) but those of Minnipa and Wudinna are not so marked, and they have accordingly been grouped as type III(11). Yaninee and Warramboo are illustrated in Figure 16, which shows clearly the 2-3 bushel advantage in yield conferred by the better soil.

2. Transitional mallee-solonetz soils; rainfall 10-13 in.

a. Barwell (69), McLachlan (70), Tooligee (82), Palkagee (71), Rudall (83), Roberts (89), Dixson (97), Smeaton (75), Pascoe (72), Campoona (76), Solomon (65), and Kelly (66) (1907-21).—The last two hundreds contain, in addition, areas of mixed mallee soils. Even though the records are comparatively short, it has been possible to establish the reality of the improvement in yield, since the soils are more fertile and the seasonal conditions more favourable. The whole set is outstanding and has been classified as type IV(11). Tooligee (0.30 bushel per acre per annum) and Palkagee (0.42 bushel per acre per annum) have remarkably high increments.

b. Boothby (90), and Yadnarie (84) (1880-84).—The light and spasmodic cropping in these hundreds during the first twenty years did not materially reduce fertility, and consequently there is no marked reaction following the first applications of superphosphate. Yields increase steadily up to 1941, following the course of type VI(10). Figure 17 contrasts the curves of Tooligee and Boothby; the superiority of the former with respect to mean yield and trend is largely due to the advantages conferred by a difference of approximately 2 in. in the rainfall.

3. Loamy mallee soils merging into red brown earths.

The occurrences of these soils are in two separate localities within zones of different rainfall.
(i) Rainfall 9-12 in.
   a. Miltalie (78), Minbrie (79), Mann (85), Hawker (86), and Playford (87) (1880-84).—The remarks here are similar to those given for Boothby and Yadnarie, all curves being of type VI(10). The result obtained for Playford is surprising, but it is readily understood when account is taken of the changes in acreage. The greatest area recorded was 8600 acres in 1913, and since then it has progressively decreased, at the same time concentrating in the north-west corner of the hundred on loamy mallee soils. Associated with this progressive retreat to the better areas is a gradual increase in mean yield, the effect of which is to reverse the curvature of the regression on time, the net result being that yield exhibits a small but real improvement, but the maximum yield was only about 6 bushels per acre.

   b. Mangalo (77) (1907).—The remarks here are similar to those given for Barwell etc., and the curve is of type IV(11).

   Mangalo and Hawker, which are illustrated in Figure 18, resemble Tooligie and Boothby respectively. The loamy mallee soil is definitely superior to the transitional phase, but rainfall is the limiting factor.

(ii) Rainfall 12-16 in.
   a. Stokes (100), Yaranyacka (101), Hutchison (105), and Louth (106) (1880).—From 1880 to 1896 only limited areas were sown to wheat, and to some extent cropping was also spasmodic. Very little deterioration occurred, so that the initial response to superphosphate is not strongly marked. All yields increase linearly, following curves of type VI(10).

   b. Shannon (93), Brooker (94), Moody (95), and Butler (96) (1897-1907).—These hundreds all possess well-defined courses of type IV(11), Shannon, in particular, having the high annual increment of 0.40 bushel per acre. The curves of Hutchison and Shannon are given in Figure 19. Comparison of Figures 18 and 19 brings out clearly the superiority of the group in the zone of higher rainfall, where all rates of increase are greater both relatively and absolutely. This small section constitutes one of the most progressive portions of the wheat belt.

4. Podsols; rainfall 16-20 in.
   a. Warrow (102), Ulipa (98), and Koppio (104) (1880).—The three curves are of type VI(10).
b. Cummins (99) and Mortlock (103) (1907).—These hundreds have been classed as type IV(11).

The series possesses an interesting feature, of which no trace is present in any other district. Neither subgroup shows an improvement in yield at the beginning of the several periods examined; in the three hundreds that were settled first, yield was maintained at 6-8 bushels per acre and did not increase until some years after the introduction of superphosphate, and in the remaining two, the improvement likewise did not follow until after an initial stationary period. For the purposes of classifying and mapping the trends, this small departure from linearity was ignored. Figure 20 illustrates the courses in Koppio and Cummins.

5. Rendzinas; rainfall 12-16 in.

a. Colton (67), Talia (68), Ward (81), and Kiana (91) (1880).—As with other districts on Eyre Peninsula, in which early settlement occurred, initial cropping made only light demands on the soil, so that no marked changes occurred in these hundreds shortly after the first applications of superphosphate. From 1896, all yields increase steadily, following curves of type VI(10).

b. Mitchell (92) (1907).—In this area the curve is of type IV(11).

The group, as a whole, has a higher rainfall than the loamy mallee soils of the Cleve district, but the annual increments in yield, although quite significant, are only of the same order as those of the latter, i.e. about 0.10 bushel per acre per annum.

6. Loamy mallee soils agriculturally similar to the desert loams; rainfall 8-10 in.

Wilton (88), Glynn (74), Warren (80), Moseley (64), and Cortlinye (63) (1907-16).—This series has been classed as type III(11), since a definite decision regarding trend has not been obtained. Moseley and Cortlinye are the only important areas in the group.

7. Solonetz; rainfall 10 in.

The only hundred concerned is James (73), which was opened for settlement in 1910. The increase in yield is small (about 0.10 bushel per acre per annum) but definite, and has been included under type IV(11).
Flinders

1. Desert loams and mixed mallee types merging into desert loams; rainfall 6-10 in.

This group includes all hundreds in Flinders that are not listed under sections 2, 3, and 4 below (1875-84).

2. Sandy mallee; rainfall 10-12 in.

Winninowie (130), Baroota (137), and Telowie (144) (1875-84).

3. Red brown earth and mixed mallee; rainfall 10-12 in.

Black Rock Plain (141), and Yongala (146) (1875-84).

In the three groups, exploitative management of the first twenty years rapidly depleted soil reserves, yields declined, and incipient erosion developed. With the beginning of the new century came a full realization that in addition to the inferior types of soil, the settler had to contend with an extremely erratic seasonal rainfall. In consequence, the boundary of the area under cultivation was withdrawn during 1902-09, and cropping confined to scattered localities in the Flinders Ranges, which possessed arable pockets of somewhat better soils with a slightly higher rainfall. Superphosphate and the retreat to the more favourable sites were the principal factors responsible for the increase in yield from 1896 to 1920, but this effect was transitory, since, with very few exceptions, even in these situations, the soils were incapable of withstanding frequent cropping. From about 1920, yields again declined, and apart from Wonoka, type V(10), and Black Rock Plain, type IV(10), the courses are of types I and II(10), depending upon local conditions. Wonoka and Black Rock Plain supply good illustrations of the effect on the trend in yield of a progressive reduction in acreage and concentration on better soils; in the latter almost the entire area occupied by the crop is red brown earth. In the majority of hundreds with type II curves the area of wheat was small and remained constant, the inference being that cultivation had been restricted to slightly better situations throughout. Palmer, Willowie, and Wonoka are contrasted in Figure 21; the type II curve of Figure 10 is that of Yongala.

4. Red brown earth; rainfall 10 in. to more than 14 in.

Pichi Richi (119), Gregory (131), Wongyarra (138), Booleroo (139), Appila (145), and Pekina (140) (1875).—After settlement, the area in each hundred increased to a point where it became stable. The initial exploitative
cropping caused yields to decline, but they recovered after the introduction of superphosphate, and under the greatly improved conditions of soil and rainfall, continued to increase up to 1941, although at diminishing rates. Pichi Richi and Wongyarra are of type V(10), and the remainder type IV(10). In Pichi Richi the area of crop has remained practically constant since 1880, and actually only part of the hundred is classed as marginal land, but for convenience in mapping this has not been indicated in Figure 12. Figure 22 shows the courses in Pichi Richi, Pekina, and Appila, and illustrates the effect of an increase in seasonal rainfall from 10 in. to 14 in. The type V curve of Figure 10 is that of Wongyarra.

**Goyder**

1. Mixed mallee; rainfall 9-12 in.

Terowie (159), and Baldina (181) (1875-84).—The history of cropping in these hundreds runs exactly parallel with that of the hundreds with type I curves in Flinders; Baldina is type I(10), and Terowie type II(10), the latter being almost identical with the curve for Yongala in Figure 10.

![Graph showing yield trends](image)

**Fig. 23**

2. Sandy mallee; rainfall 10-13 in.

Pirie (151), Wandearah (160), Napperby (152), Mundoora (167), and Wokurna (174) (1875-84).—In all districts the yields show the characteristic decline prior to 1896, and subsequent recovery which is transitory except in Wokurna. Rainfall increases from 10 in. to 13 in. in the order in which the hundreds are named, and the trends follow, in the sequence of types I, I, II, II, and IV(10), with improvement in the soils. The course in Pirie is the type I curve of Figure 10, Wandearah is closely similar, with a maximum of 11 bushels per acre, and Napperby, Mundoora, and Wokurna are given in Figure 23. Winninowie, Baroota, and Telowie (from Flinders) also fall properly into the sequence, their curves resembling that of Napperby.

3. Loamy mallee; rainfall 11-16 in.

Crystal Brook (161), Narridy (162), Yangya (156), Koolunga (169), Boucaut (176), Cameron (182), Everard (183), and Blyth (184) (1870-84).—All yields exhibit marked deterioration prior to 1896 and the subsequent recovery, but the curves vary according to the local conditions. Everard is of type I(10), and Boucaut type III(10). The soils of Everard are variable, and often poorer than the average grade of loamy mallee, while in Boucaut a small tract of inferior
stony mallee occurs; in addition, both hundreds are endoreic zones in which problems, associated with the development of salinity in the surface soils, have arisen. The influence of the more fertile class of soil is apparent in the remaining hundreds, all of which are of type IV(10). Figure 24 shows the courses in

![Graph](image-url)

Fig. 24

Everard and Narridy, and the type III curve of Figure 10 is that of Boucaut.

4. Red brown earth; rainfall 12-18 in.

Tarcowie (149), and Mannanarie (150) (1870-75); Howe (153), Booyoolie (154), Caltowie (155), Belalie (157), Whyte (158), Bundaleer (163), Reynolds (164), Anne (165), Red Hill (168), Barunga (175), Yackamoorundie (170), Hart (177), Ayers (172), and Andrews (171) (1866-75); Milne (178) and Hanson (179) (1860-70); Kingston (173), Kooringa (180), and Hallett (166) (1875-84); and Clare (185) (1869).—All trends display remarkably high rates of increase for some ten years after the initial applications of superphosphate, the general curve being type IV(10), but there are several exceptions. Whyte, type II(10), is comprised partly of mixed mallee soils, and just over half the area under wheat lies in a zone between the 10 in. and 12 in. isohyets. The acreage has been maintained throughout and this is the main factor underlying the contrast with Black Rock Plain. Ayers, Hanson, Hallett, Kingston, and Kooringa follow curves of type III(10). The best soils of these five hundreds are devoted principally to lucerne, and wheat is relegated to the lower slopes of the hills on shallow residual red brown earths, which are less fertile than the
alluvial types of Belalie and Caltowie, for example. Hallett, Kingston, and Kooringa are extreme in this respect, while Ayers and Hanson carry an intergrade soil between the extremes. Whyte and Bundaleer are contrasted in Figure 25. Clare follows a course of type V(10).

**Light**

1. Mixed mallee
   (i) Rainfall 6-10 in.
      Bright (192), and Bundey (193) (1880); and Bower (197) (1884).—This trio forms part of the worst section of the wheat belt. The curves are type I(10), and the history of cropping is similar to that of hundreds in Flinders with the same form of trend.
   (ii) Rainfall 10-14 in.
      English (196), Neales (204), and Dutton (213) (1860-70).—In these cases the mean yields are considerably greater, and the curves are type II(10). Bower, Neales, and English are compared in Figure 26, which shows clearly the effect of the additional 4 in. seasonal rainfall. The course of yield in Dutton is almost identical with that of English.

![Fig. 26](image)

2. Sandy mallee; rainfall 10-14 in.

   Inkerman (198), Balaklava (199), Hall (188), Goyder (186), and Stow (187) (1860-70).—In Inkerman, where conditions are similar to those of Mundaora, the curve is of type II(10) and falls properly into sequence with other members of the sandy mallee group immediately to the north. Problems associated with the development of salinity in the surface soils similar to those in Boucaut, also occur in Stow, and the resulting curve is of type III(10). The remaining hundreds are of type IV(10). Figure 27 gives the trends of Inkerman, Stow, and Balaklava.

3. Loamy mallee; rainfall 11-14 in.

   Port Gawler (207), Dublin (205), Grace (206), Dalkey (200), and Mudlaurra (208) (1850-70).—The first four hundreds provide, in the order given, a sequence of improving variants of type IV(10), and Mudlaurra is type VI(10). In the latter, wheat was the dominant crop during the early years, reaching its peak in the decade 1870-80, when nearly 30,000 acres were cropped. The area was reduced to 10,000 acres by 1896, and since then has varied about this value. The general tendency has been to pass from wheat as
the major enterprise to mixed farming, with an increase in the number of stock carried, accompanied by an increase in the length of rotations.

4. Red brown earth; rainfall 14-18 in.

Upper Wakefield (189), Stanley (190), Alma (201), Saddleworth (194), Gilbert (202), Waterloo (195), Julia Creek (203), Kapunda (211), Light (209), Belvidere (212), Nuriootpa (210), Moorooroo (214), and Jellicoe (215) (1850-66); and Apoinga (191) (1866-70).—Apoinga and Belvidere are of type III(10). The former is a member of the series Hallett etc., for the same reasons as given previously, while in the latter, vineyards occupy the best soils and wheat is cropped on intermediate grades of red brown earth resembling those of Ayers and Hanson. Alma and Nuriootpa follow courses of type VI(10), Moorooroo is of type V(10), and the remainder type IV(10). The position with respect to wheat as the major crop has undergone a radical change in Nuriootpa and Alma, more particularly in the former. In both hundreds the area decreased from its maximum, about 25,000 acres, attained during 1870-80, and by 1896 had fallen to 10,000 acres. With the appearance of superphosphate, the area increased to 15,000 acres in Alma, and remained approximately constant up to 1941. This hundred possesses particularly good soils, and with the increase in the number of stock carried there has been a trend to mixed farming under longer crop rotations. On the other hand, in Nuriootpa the area of crop was reduced still further, until it roughly stabilized at 5000 acres. During the period under review, the area devoted to vineyards has increased, and wheat has been replaced as the major crop, practically all of it having been produced under mixed-farming conditions.

Mudlawirra, Alma, and Nuriootpa are illustrated in Figure 28.

Yorke

1. Sandy mallee; rainfall 12-13 in.

Wiltunga (217), and Ninnes (220) (1875-84).—These two hundreds are situated at the southern extremity of the sandy mallee zone running parallel with the eastern coastline of Gulf St. Vincent. The curves are type IV(10) and follow in sequence after Wokurna in conformity with the higher rainfall and improvement in the soils.
2. Loamy mallee; rainfall 12-16 in.  
Maitland (225) (1870-75); and Tickera (216), Wallaroo (218), Kadina (219), Tiparra (222), Kulpata (221), Clinton (223), Kilkerran (224), Wuraltee (227), Cunningham (226), Muloowurtie (228), Koolyurtie (229), and Curramulka (230) (1875-84).—In Kilkerran, salinity problems have developed as in Boucaut and Stow, and the yield follows a curve of type III(10). Muloowurtie is type VI(10), and although first settled during 1875-84, extensive development has only occurred in recent years, the effect of a progressive introduction of virgin land being to reverse the curvature of the regression on time, and thus maintain the rate of increase in yield. The results for Maitland, type II(10), with a maximum in 1938, and Curramulka, type V(10), in which the trend had nearly reached zero in 1941, are of far-reaching importance, and are directly ascribable to intensive cropping of cereals in the area. The remaining hundreds are type IV(10). Maitland, Tiparra, Curramulka, and Muloowurtie are illustrated in Figures 29 and 30.

![Graph](image1)

**Fig. 29**

3. Rendzina; rainfall 14-16 in.  
Minlacowie (231), Dalrymple (235), Melville (236), Moorowie (234), Para Wurlie (233), and Ramsay (232) (with some sandy mallee) (1870-80).—Moorowie and Ramsay are type IV(10), Para Wurlie is type II(10), and the remainder type V(10). The curve for Para Wurlie is an extreme variant of type II(10) in which the trend reached zero in 1940. Trace-element deficiencies are known to occur in this locality (*vide infra*).

As in southern Flinders and Goyder, the yields of all hundreds in Light and Yorke declined markedly during the period of cropping prior to 1896, and in general showed very high rates of recovery for some years after the initial applications of superphosphate. The group of four regions constitutes that part of the wheat belt which suffered most severely under the stringent conditions of cropping prior to 1896.

**Sturt**

1. Red brown earth; rainfall 12-14 in.  
Monarto (263) and Tungkillo (268) (from Adelaide) (1860); and Freeling (269) (from Fleurieu) (1862).—In these hundreds there are occurrences of mixed mallee soils, but the bulk of the wheat is grown on red brown earth, and through—
out the long history of cropping none of them has carried more than 3-5 thousand acres of wheat. The types are Monarto and Freeling VI(10), and Tungkillo V(10). Figure 31 illustrates Monarto.

2. Sandy mallee; rainfall 9 in.

Forster (261), the only hundred concerned, was opened in 1884. Yields show the characteristic decline prior to 1896, and the subsequent temporary recovery. The course of yield is type II(10), closely similar to the curve for Gordon in Figure 34.

3. Stony mallee; rainfall 8-12 in.

a. Ridley (260), Nildottie (257), Younghusband (262), Burdett (265), and Seymour (267) (1890).—The remarks here are similar to those made for Forster, all curves being of type II(10).

b. Ettrick (266) (1910).—The trend of yield during the shorter period of cropping in this hundred resembles the first phase of the remainder on this soil group, and has accordingly been classified as type III(11).

4. Mixed mallee; rainfall 8-12 in.

Bagot (256), Angas (258), Finniss (259), and Mobilong (264) (1862-75).—The courses of yield, which are of type II(10), are similar to those of English, Neales, and Dutton, on the same class of soil. Finniss is illustrated in Figure 32, and the curve for Mobilong is almost identical.

Pyap

1. Stony mallee; rainfall 6-10 in.

a. Anna (250), Brownlow (243), and Beatty (237) (1870-84).—These hundreds, together with Bagot from Sturt, Baldina from Goyder, and Bright, Bundey, and Bower from Light, comprise the worst section of the wheat belt. The three type I(10) curves are similar to that of Bower in Figure 26.

b. Cadell (238), Murbko (244), Paisley (251), and Bakara (252) (1896); and Mantung (253) (1909).—Yields of the first four hundreds show the expected increase, but as with all other mallee soils under similar conditions of rainfall, this effect is temporary. The curves are all of type II(11). Mantung, with its shorter cropping history, has improved slowly, following a course similar to the first phase of the curves in the older districts. The trend is not significant and has been classed as type III(11). The curves of Cadell and Mantung are given in Figure 33.
2. Sandy mallee; rainfall 6-8 in.

Waikerie (245) (partly stony), Holder (246), Moorook (247), Gordon (249), Pyap (254), and Bookpurnong (255) (1896); and Markaranka (239), Parcoola (241), and Pooginook (240) (1913).—The remarks here are similar to those of the previous section. Waikerie is type I(11), the next five are type II(11), and the last three type III(11). The curve for Gordon is given in Figure 34.

3. Mixed mallee; rainfall 6-8 in.

Murtho (242) and Paringa (248) (1896).—The curves are type I(11) and remarks similar to those above.

Throughout the region considerable reductions have been made in acreage since 1930, the nett effect of which has been to reduce the rate of decline in yield.

**Pinnaroo**

1. Sandy mallee; rainfall 8-10 in.

Bowhill (270) (with some stony and transitional mallee) (1896); and Bandon (271), Chesson (272), Mindarie (273), Allen (274), Kekwick (275), and McGorrery (276) (1907-19).—The curve for Bowhill is type II(11); and the remainder are of type III(11); remarks are similar to those above. McGorrery is shown in Figure 34.

2. Transitional mallee-solonetz; rainfall 10-12 in.

Vincent (277), Wilson (278), McPherson (279), Hooper (281), Marmon Jabuk (282), Molineux (283), Sherlock (288), Roby (289), Peake (290), Price (291), Cotton (284), Bews (285), Parilla (286), Pinnaroo (287), Peebinga (280), and Allenby (292) (1907-19).—The general curve is type IV(11) with the exception of Peebinga, Roby, and Sherlock, which are type III(11). This soil group is outstanding, and the contrast between it and neighbouring mallee types to the north is just as strongly marked as on Eyre Peninsula. The courses of yield in Pinnaroo and Roby are illustrated in Figure 35.

3. Solonetz; rainfall 14 in.

The only hundred concerned is Livingston (293), which is also of type IV(11) and was opened in 1907.

**Tatiara**

1. Solonetz; rainfall 15 in.

Stirling (294) (1889).—The curve is type VI(10), and the marked superiority of this hundred over Livingston is due to the fact that wheat is confined to a
section in which the solonetzic soils are mixed with a rendzina-terra rossa complex of greater fertility.

2. Wimmera grey loam; rainfall 15 in.

Tatiara (296) and Wirrega (295) (1876 and 1877).—In both hundreds yields declined slightly under the cropping prior to 1896, but after the introduction of superphosphate increased steadily up to 1941, following curves of type VI (10). Stirling and Wirrega are contrasted in Figure 36, which shows the superiority of the Wimmera loam; the difference is even more marked when a comparison is made between Tatiara, the type VI curve of Figure 10, and Stirling.

The remarkable progress made in these districts agrees with observations made by Wadham and Wood (1939) on the Victorian counterpart of the soils.

(d) Discussion of Trends

It must be emphasized that this study is, by nature, only a broad survey. Obviously, with respect to any particular hundred there is, on the one hand, a set of factors tending to increase yields, and on the other, a set tending to decrease them. The observed trend is the resultant of their effects, and because of the nature of the data they are completely confounded and incapable of separate assessment; in fact, it is not even possible to enumerate either set exhaustively. But in viewing the matter broadly, some indication can be given of the major contributors in the two directions. Several instances have already been given in Section V (c).
On the positive side the principal factors are:

1. Maintenance of an adequate phosphorus and nitrogen supply.
2. Adoption of cultural practices suited to various types of soil.
3. Use of improved varieties adapted to the particular conditions of different localities.
4. Maintenance of the physical condition of the soil.

On the other hand, decreases can be unhesitatingly ascribed to a reduction of fertility consequent upon agricultural exploitation of the soils through overcropping in short-term rotations. As pointed out above, this has proceeded so far in some areas that it outweighs the beneficial effects of recent advances, and results in a progressive decline. In other localities, although yield was still increasing in 1941, it would appear that farming practices in vogue were none the less exploitative, since rates of increase were being rapidly decelerated and yields were not as high as would be anticipated considering the nature of the soils, the seasonal rainfall, and the potentialities of the latest varieties at the time. Further reference is made to this point below.

The decline in fertility is attributable to (i) a cumulative deficiency of one or more essential elements, and (ii) a loss of soil structure. Each of these may exert its effects directly or indirectly.

(1) Cumulative Deficiencies.—Considering the soils of the wheat belt generally, no extensive quantitative evidence has hitherto been presented to show that there is a cumulative deficiency of any element which is essential in the assimilatory processes of the wheat plant, such as occurred with phosphorus. The paramount importance of nitrogen in this connection was obscured until about fifteen years ago by the fact that all experimental work had been conducted on fallowed land under conditions which were not conducive to substantial responses from nitrogenous fertilizers (Richardson and Gurney 1933). The necessity of fallowing for securing high returns received general recognition early in the development of the industry, and the practice was adopted widely. For many years its greatest advantage was considered to be conservation of water that fell in the fallow season, but latterly this view has changed. Observations which were assembled and reviewed by Prescott (1933) showed that nitrate accumulation is at least equally as important as moisture conservation and the extermination of weeds. It is known that the production of nitrate in a fallow is considerable (Prescott loc. cit.), and under optimal conditions is sufficient to meet the needs of heavy crops, i.e. 50-60 bushels per acre. Since, for example, a 15 bushel crop removes approximately 20 lb. nitrogen per acre in its grain and straw, and to this must be added the amounts lost in other ways, the maintenance of fertility, provided no other factor is limiting, rests upon the replacement of this nitrogen. Nitrogenous fertilizers are not used, so that unless natural sources exist to compensate the loss, it must be borne by the nitrogen reserves of the soil.
Three contributors that may be considered in this connection are:
1. Non-symbiotic nitrogen fixation.
2. Symbiotic fixation with legumes.
3. Nitrogen introduced in rain water.

With respect to the first, the weight of evidence at the present time points to the fact that it is not of any consequence in the soils of the wheat belt. Thus Beck (1935), after examining South Australian soils, concluded that Lewcock's (1925) claim of the universal distribution of *Azotobacter* was not substantiated, and even in soils containing the organism the numbers present were so small that the amounts of nitrogen fixed would be negligible. Swaby (1939) working with Victorian soils found *Azotobacter* comparatively rare, and reached the same conclusion as Beck. On the other hand, *Clostridium butyricum* was much more widely distributed, and present in greater numbers, but environmental conditions in the wheat soils are not suitable for the development of this anaerobe to the point where it could fix appreciable amounts of nitrogen. Finally, Jensen (1939), in reviewing current work at the time on New South Wales soils, concluded that non-symbiotic fixation is only "a minor and mostly insignificant factor in maintaining the nitrogen content of soils under wheat cultivation." Recent observations made by Clarke and Marshall (1947) are also relevant in this connection; and at the same time demonstrate forcibly the outstanding weakness of the fallow-wheat rotation. These authors determined the reduction in the nitrogen content (expressed as a percentage of air-dry soil passing a 2 mm. sieve) of two slightly different red brown earths, after various periods of cultivation. The total declines in surface soils (top 4 in.) were 0.158 to 0.094 per cent. and 0.222 to 0.135 per cent. after 16 and 20 years, respectively, of cropping in a fallow-wheat rotation with superphosphate applied to the crop. The upper limit of each range is for virgin soil, and both reductions, of which the greater part occurred in the first five years, are statistically significant. Declines in subsurface soils were not significant. No legumes developed on either site, and consequently any nitrogen which may have been added to the soils came from other sources. Such contributions, if they existed, must, however, have been very small, since the ratio of carbon to nitrogen in these soils is approximately 12, thus making the nitrogen content a fairly accurate index of their organic matter status. It would appear then that the nitrogen withdrawn by successive crops was derived principally from the organic reserves of the soils.

Symbiotic fixation of nitrogen with legumes has undoubtedly been of some importance in certain areas of the wheat belt; further reference to this point is relegated to a later stage of the discussion.

Jensen (loc. cit.) quotes amounts of 3-4 lb. nitrogen per acre per annum in rain water, but these are trivial.

The soils of the South Australian mallee have been studied by Prescott and Piper (1932), and the red brown earths by Piper (1938). The percentage of nitrogen in the surface soils of the mallee group ranges from low (less than 0.10 per cent.) to moderate (0.10 to 0.30 per cent.) in passing from light textured sandy types to the heavier loams, with an average of 0.06 per cent., but texture
and percentage nitrogen are not strongly associated; 87 per cent. of surface soils examined contained less than 0.10 per cent. nitrogen, and 83 per cent. of subsoils less than 0.05 per cent. In the red brown earths, the proportion of nitrogen varied from low to moderate, with an average of 0.10 per cent. for surface soils, 60 per cent. of which contained less than the average. The first 9 in. was taken in this group as surface soil, and this accounts for the fact that the average value lies at the lower extremity of the range for moderate amounts. The original reserves of nitrogen in the principal wheat soils are thus, at best, only moderate, and consequently it would not be surprising that an exploitative system of cropping has largely exhausted them.

Reference may be made to recent work on trace-element deficiencies, as this may also have a bearing on the nitrogen problem. The malady known as "coast disease" of sheep occurs in parts of South Australia, and has been shown to result from a dual deficiency of copper and cobalt in the fodder consumed by animals depastured in the affected areas (Marston, Lee, and McDonald, 1948a, 1948b). Other regions in which a deficiency of copper is not complicated by one of cobalt have been identified. On these much greater areas, the deficiency of copper varies in degree which is manifested by the animal in a range of symptoms, the first to appear being a lesion in the wool which is characteristic, specific, and easily discernible (Marston, Lee, and McDonald loc. cit.). The occurrence of these nutritional disorders in stock has led to intense work on the mineral requirements of oats and pasture plants, including legumes, in certain isolated areas (Riceman 1946, 1948), where essential trace elements, in particular copper and zinc, as well as phosphorus and nitrogen, are in extremely short supply. No widespread deficiencies have been observed with cereals, but observations made by Lee (personal communication, 1948) have shown that, except for the greater part of Flinders, copper deficiency, as indicated by the occurrence of lesions in wool, occurs throughout the portion of South Australia illustrated in Figures 8 and 12 and the extreme south-eastern section not included in the figures. The density of occurrence is greatest on the littoral calcareous dunes and adjacent areas, and is gradually reduced in passing from the mallee soils and genetically related types (Crocker 1946) to the red brown earths. As the requirements of the animal relative to those of the plant are enormous, it is much more sensitive and this would account for the observed facts. On the other hand, it is known that copper is essential in nitrification, and the possibility exists that in some areas after a period of cropping the originally low copper status of the soils has been reduced to a point where nitrifying organisms react to deficiencies which do not restrict the wheat plant. If this is so, it would tend to make nitrogen a limiting factor for wheat production; and of the main wheat soils, the mallee types are the most likely to be affected. Other elements are also required in nitrification, but particular reference is made only to copper in view of its known deficiencies.

There are also indications that deficiencies of certain elements are causing indirect effects by restricting symbiotic fixation of nitrogen. Trumble (personal communication, 1948), using various legumes as test plants, has obtained definite
responses in yield to the elements potassium, copper, zinc, molybdenum, boron, and manganese at widely dispersed points of the wheat belt, either singly (potassium, molybdenum, zinc) or in certain combinations.

The extent to which these factors operate in limiting the nitrogen supply can, however, only be resolved by an extensive set of field trials.

(ii) *Loss of Soil Structure.*—Frequent cropping leads also to deterioration of soil structure and, indirectly through this, to losses of plant nutrients by erosion. The reduction in water-stable aggregates originally present in virgin soil by cultivation has been well established, and it will suffice to refer to the work of Clarke and Marshall (loc. cit.). Changes in water-stable aggregation of red brown earth surface soils, resulting from increasing periods of cultivation up to twenty years, were measured, and significant decreases found in all cases. The major part of the decline took place in the first five years of cultivation, and the total declines ranged from 42 to 69 per cent. of the aggregates in virgin grassland. The decrease results directly from the mechanical action of tillage, and indirectly through the decomposition of the organic matrix during fallowing. The effect on soils of heavy texture is to reduce their absorptive and retentive powers in coping with heavy rains; surfaces tend to set hard, causing uneven germination and making cultivation more difficult. Piper (loc. cit.) records such instances in the zone of the red brown earths. The most serious consequence, however, is that water erosion supervenes and may advance to its worst form — sheet erosion. Considerable areas in Flinders, Goyder, and Light have been eroded in varying degree (Rural Reconstruction Commission 1944), and the position in the hundred of Belalie may be taken as typical of a large proportion of the best agricultural land:

<table>
<thead>
<tr>
<th>Degree of Erosion</th>
<th>Per Cent. of Surface Soil Remaining</th>
<th>Per Cent. of Total Arable Land</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slight</td>
<td>&gt; 75</td>
<td>24</td>
</tr>
<tr>
<td>Moderate</td>
<td>25-75</td>
<td>69</td>
</tr>
<tr>
<td>Severe</td>
<td>&lt; 25</td>
<td>7</td>
</tr>
</tbody>
</table>

On light textured sandy soils, removal of the original vegetal cover followed by frequent cropping has led to sand drift by aeolian action, the principal regions concerned in this respect being Sturt, Pyap, and northern Pinnaroo.

(iii) *General Relation between Form of Trend and Nitrogen Status of the Soils.*—The orderly geographical distribution of the various types of trend is striking, and accords generally with the view that after the deficiency of phosphorus has been overcome the progressively diminishing nitrogen status of the soils is a dominant factor influencing the form of the curves.

On sandy, stony, and mixed mallee soils, and related types that were opened in 1896 or several years later, the onset of a decline appears after 20-25 years of cropping with adequate supplies of superphosphate, and by 1941 yield in the majority of hundreds concerned had fallen to approximately the value it had attained at the time of settlement. In these soils, the proportion of nitrogen in their virgin state is low and the losses sustained by exploitation during the pioneer-
ing years and later cropping, together with those due to erosion where it has occurred, are great enough to exhaust the reserves in approximately 45 years.

Similar mallee types, and the desert loams which were settled between 1875 and 1896, had been largely abandoned after 10-20 years, and consequently are not represented among the curves of Figure 10. After the advent of superphosphate, the remaining small isolated areas of slightly better soils carried on for a further 20 years, when a second decline supervened and yield fell gradually to its value at the beginning of the century (hundreds with curves of type I(10)). In these soils exhaustion thus occurs after 55-65 years of cropping.

Table 3

<table>
<thead>
<tr>
<th>Station</th>
<th>Length of Record (years)</th>
<th>&gt;14</th>
<th>12-14</th>
<th>10-12</th>
<th>8-10</th>
<th>6-8</th>
<th>&lt;6</th>
<th>Mean Apr.-Nov.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fowler's Bay</td>
<td>69</td>
<td>6</td>
<td>8</td>
<td>15</td>
<td>25</td>
<td>12</td>
<td>3</td>
<td>10.22</td>
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<tr>
<td>Ceduna</td>
<td>39</td>
<td>1</td>
<td>4</td>
<td>7</td>
<td>10</td>
<td>13</td>
<td>4</td>
<td>8.89</td>
</tr>
<tr>
<td>Petina</td>
<td>38</td>
<td>4</td>
<td>8</td>
<td>12</td>
<td>11</td>
<td>1</td>
<td>2</td>
<td>10.68</td>
</tr>
<tr>
<td>Costlineye</td>
<td>26</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>8</td>
<td>7</td>
<td>1</td>
<td>9.66</td>
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<tr>
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<td>2</td>
<td>6</td>
<td>9</td>
<td>18</td>
<td>21</td>
<td>9</td>
<td>8.51</td>
</tr>
<tr>
<td>Hawker</td>
<td>64</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>16</td>
<td>11</td>
<td>15</td>
<td>9.25</td>
</tr>
<tr>
<td>Hammond</td>
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<td>4</td>
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<td>18</td>
<td>8.14</td>
</tr>
<tr>
<td>Orroroo</td>
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<td>15</td>
<td>15</td>
<td>17</td>
<td>7</td>
<td>10.00</td>
</tr>
<tr>
<td>Terowie</td>
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<td>7</td>
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<td>11</td>
<td>17</td>
<td>14</td>
<td>6</td>
<td>9.96</td>
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<tr>
<td>Sandleton</td>
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<td>4</td>
<td>20</td>
<td>9</td>
<td>20</td>
<td></td>
<td>7.54</td>
</tr>
<tr>
<td>Morgan</td>
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<td>2</td>
<td>9</td>
<td>16</td>
<td>24</td>
<td></td>
<td>6.67</td>
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<td>Loxton</td>
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<td>8.01</td>
</tr>
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<td>Copeville</td>
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<td>8</td>
<td>7</td>
<td>7</td>
<td></td>
<td>8.82</td>
</tr>
</tbody>
</table>

All diagrams given above, which refer to these districts, indicate that the maximum yields obtained under average rainfall are extremely low; considerable effort would have to be expended to increase them by 50 per cent. Without doubt, deterioration could be arrested and fertility restored in certain localities, but considering the areas generally, improvement would be of limited extent, as the steps taken must ultimately depend upon rainfall and its reliability. At the moment, research is proceeding on this vitally important feature of the climate, but no detailed quantitative data are available for the areas concerned. The approximate analysis of records from typical stations, set out in Table 3, illustrates the extremely hazardous nature of the seasonal rains, and requires no further comment, except perhaps to add that all stations are presented in the most favourable light, since the average effective rainfall at each is only slightly greater than 5 in. (vide Trumble loc. cit., map 2).

As pointed out above, the large tracts of these particular mallee soils that have been developed recently appear to be following courses similar to the districts with longer records, and although yields were still slowly increasing at
the close of the period under review, it can be confidently anticipated that if cropping is continued under the old system, they will eventually decrease.

In an extensive and detailed report, the Pastoral and Marginal Agricultural Areas Inquiry Committee (loc. cit.) reviewed all enterprises within the marginal areas, and after examining the economics of wheat production both from the point of view of direct returns from wheat and that of indirect returns from sidelines, submitted a strong case for the abandonment of wheat-growing as the major operation, and hence mixed farming, in these regions. The Committee concluded that the worst portions of the marginal lands “within which it is impracticable to continue with any system of land use that involves even periodic cropping for grain, must of necessity be turned over to sheep grazing (with perhaps a few cattle) on an extensive scale, as no other proposition can provide the basis for security . . .” Apart from those hundreds which were omitted from consideration in the present analysis for reasons given in Section III(a), and ten minor exceptions, of which every one can be given adequate account, it will be observed in Figure 12 that the yields of all hundreds designated as marginal by the Committee follow courses of types I and II(10) or I, II, and III(11), and this result lends material support to their conclusion. The marginal boundaries as given in Figure 12 have been chosen to conform with the territorial unit which forms the basis of this investigation and should be regarded as indicating the approximate position of the line. Wannamana, Kappakoola, Warramboo (Eyre), and Vincent, Wilson, McPherson (Pinnaroo) constitute two doubtful areas. Their mean yields were low, but their rates of increase were quite definite and constant up to 1941, and consequently additional data must be examined before final judgment is passed. The remaining exceptions have been discussed in Section V(c).

Next in order are mallee soils situated in an intermediate zone of 10-14 in. seasonal rainfall. The hundreds concerned are Ripon, Scott, Murray (Nuyts), Telowie, Yongala (Flinders), Pirie, Napperby, Wandearah, Mundoora, Whyte, Terowie, Everard (Goyder), English, Neales, Dutton, Inkerman (Light), Finniss, Mobilong, Burdett, Ettrick, and Seymour (Sturt), which, except for Everard and Inkerman, are either contiguous or nearly so with the inner marginal boundary. In these areas the decline may not supervene until after 25-35 years of cropping with an ample supply of superphosphate, and except for Pirie its magnitude is not as great relatively as in the previous cases.

Thirdly, follow the heavier loamy mallee soils with a rainfall of 12 in. or more, and the red brown earths in Flinders, Goyder, Yorke, and Light. The dominant form of trend in this group of 78 hundreds is type IV(10). More significant observations are, however, that there are only six courses of type VI(10), each of which is characterized by special circumstances, and the presence of a type II(10) curve in Maitland, a district that has always been regarded as one of the best centres for cereal culture. The yields of barley in Maitland follow a similar course, thus confirming the result for wheat. It is of some moment also that the rate of increase in yield of the type V(10) curve of Curramulka, had very nearly reached zero by 1941. These observations, when
coupled with the widespread advance of declining yields in the submarginal zone, provide a timely and salutary warning that the existing cropping systems must be altered radically to prevent further deterioration.

Since this group constitutes the heart of the industry, from which approximately 80 per cent. of the total harvest is gathered, it is worth while furnishing additional detail regarding the trends. Table 4 sets out the rates of increase in yield at four points of the period 1896-1941, together with the yield of 1941, adjusted for rainfall. It must be recognized that the production of the soil-

<table>
<thead>
<tr>
<th>Region* and Hundred</th>
<th>Rate of Increase of Yield (bush./ac./an.)</th>
<th>1941 Yield (bush./ac.)</th>
<th>(bush./ac./in. seasonal rainfall)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1900</td>
<td>1911</td>
<td>1921</td>
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<td><strong>Flinders</strong></td>
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<td>0.25</td>
<td>0.18</td>
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<td>0.36</td>
<td>0.27</td>
</tr>
</tbody>
</table>

* The name of the region is printed in italics.
<table>
<thead>
<tr>
<th>Region* and Hundred</th>
<th>Rate of Increase of Yield (bush./ac./an.)</th>
<th>1941 Yield (bush./ac.) (bush./ac./in. seasonal rainfall)</th>
</tr>
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<tbody>
<tr>
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<td>1911</td>
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<tr>
<td>Alma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gilbert</td>
<td>0.65</td>
<td>0.30</td>
</tr>
<tr>
<td>Julia Creek</td>
<td>0.51</td>
<td>0.22</td>
</tr>
<tr>
<td>Dublin</td>
<td>0.42</td>
<td>0.18</td>
</tr>
<tr>
<td>Grace</td>
<td>0.51</td>
<td>0.22</td>
</tr>
<tr>
<td>Port Gawler</td>
<td>0.39</td>
<td>0.17</td>
</tr>
<tr>
<td>Mudlawirra</td>
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<td></td>
</tr>
<tr>
<td>Light</td>
<td>0.54</td>
<td>0.23</td>
</tr>
<tr>
<td>Nuriootpa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kapunda</td>
<td>0.54</td>
<td>0.24</td>
</tr>
<tr>
<td>Belvidere</td>
<td>0.75</td>
<td>0.16</td>
</tr>
<tr>
<td>Moorooroo</td>
<td>0.20</td>
<td>0.19</td>
</tr>
<tr>
<td>Jellicoe</td>
<td>0.36</td>
<td>0.15</td>
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<tr>
<td>Tickera</td>
<td>0.49</td>
<td>0.26</td>
</tr>
<tr>
<td>Wiltunga</td>
<td>0.53</td>
<td>0.27</td>
</tr>
<tr>
<td>Kadina</td>
<td>0.52</td>
<td>0.25</td>
</tr>
<tr>
<td>Ninnes</td>
<td>0.59</td>
<td>0.30</td>
</tr>
<tr>
<td>Kulparka</td>
<td>0.56</td>
<td>0.26</td>
</tr>
<tr>
<td>Tiparra</td>
<td>0.68</td>
<td>0.38</td>
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<tr>
<td>Clinton</td>
<td>0.55</td>
<td>0.28</td>
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<tr>
<td>Kilkerran</td>
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<td>0.28</td>
</tr>
<tr>
<td>Maitland</td>
<td>0.72</td>
<td>0.51</td>
</tr>
<tr>
<td>Cunningham</td>
<td>0.63</td>
<td>0.35</td>
</tr>
<tr>
<td>Wauraltee</td>
<td>0.62</td>
<td>0.31</td>
</tr>
<tr>
<td>Muloowurtie</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Koolywurtie</td>
<td>0.56</td>
<td>0.26</td>
</tr>
<tr>
<td>Curramulka</td>
<td>0.64</td>
<td>0.48</td>
</tr>
<tr>
<td>Minlacowie</td>
<td>0.44</td>
<td>0.35</td>
</tr>
<tr>
<td>Ramsay</td>
<td>0.52</td>
<td>0.25</td>
</tr>
<tr>
<td>Para Wurie</td>
<td>0.65</td>
<td>0.48</td>
</tr>
<tr>
<td>Moorowie</td>
<td>0.60</td>
<td>0.29</td>
</tr>
<tr>
<td>Dalrymple</td>
<td>0.37</td>
<td>0.32</td>
</tr>
<tr>
<td>Melville</td>
<td>0.31</td>
<td>0.30</td>
</tr>
</tbody>
</table>

*The name of the region is printed in italics.*
rainfall combination is limited, so that ultimately yield must slowly approach an asymptote. Comparison of the 1941 yields in Table 4, expressed as bushels per acre per inch seasonal rainfall, with the known potentialities of the most recent varieties at that time, which under favourable field conditions would yield 1½ to 2½ bushels per acre per inch, shows clearly that the retardation is due to causes other than those imposed by natural limitations. It will be observed that only 11 hundreds exceed the lower limit of 1½ bushels per acre per inch. Actually the figures given are slightly exaggerated, since no account has been taken of the amount of water conserved by falling. This depends on characteristics of the rainfall distribution, physical properties of the soil, and depth of penetration of the plant's root system, and in some places may exceed the equivalent of 4 in. of rain.

With these hundreds also, there can be no doubt that the nitrogen content of the soils is being depleted, as indicated by the progressive retardation in the course of yield, but their originally greater reserves and the regular appearance of improved varieties during the past 20-30 years have been major factors in preventing the occurrence of a decline in many of them. Under the better conditions of rainfall, continual use of superphosphate has encouraged the development of annual legumes, so that, in addition, symbiotic fixation of nitrogen has made appreciable contributions toward the maintenance of the nitrogen supply, but its effects cannot be assessed accurately without further information.

Finally, there are parts of southern Nuyts, Eyre, Pinnaroo, and Tatiara, the principal soils being sandy and loamy mallee, transitional mallee-solonetz, and Wimmera grey loam. In all hundreds the trends are either type VI(10) or type IV(11), these forms being directly attributable to the advances made in the past 40 years. The important point, however, is that the effects are manifested in this manner because a large proportion of the original nitrogen reserves still remains owing to the comparatively recent development of the areas. The Wimmera grey loam is a special case, noted for its high organic matter content, and constituting one of the most fertile wheat soils of Australia. The progress made is remarkable, despite the exploitative nature of the cropping system, and to date there is no conclusive evidence of physical deterioration. Of the remaining three soil types, the only one represented in places where cropping began prior to 1896 is loamy mallee. The marked contrast between the forms of trend in Figures 24 (Narridy), 29, 30 (Curramulka), and Figures 19, 30 (Muloowurtie) is largely an expression of this difference, the longer cropping history of the hundreds in the first group having led to a greater depletion of the nitrogen reserves. The experiences gained on the older areas provide a warning for the four soil types, particularly sandy mallee and transitional mallee-solonetz, as these are more likely to be affected first.

(iv) Restoration and Maintenance of the Nitrogen Status.—In these regions, with their comparatively reliable seasonal rains, the economic restoration and maintenance of the nitrogen supply can be effected by lengthening rotations to include several years of forage crops and/or temporary pasture which embody
A legume and are capable of supporting maximal numbers of livestock. At the same time, this system periodically rebuilds soil structure.

A classical illustration is provided by the analysis of an accurate record of yield taken near Saddleworth. The property concerned passed into the hands of the present owners in 1897, after having been worked on a fallow-wheat rotation, probably for many years. In 1897 a three course rotation, fallow-wheat-pasture, was adopted and retained until 1924. The pasture phase of this rotation was replaced by oats in 1925, and shortly after, three longer rotations were introduced, namely,

- fallow-wheat-oats-fallow-wheat-oats (grazed)-wheat (second fallow replaced occasionally by peas),
- fallow-wheat-peas-wheat-oats-pasture,
- fallow-wheat-oats-pasture,

in which the pasture contained burr clover as a constituent species. Sheep and cattle have been carried on the property since 1897, and superphosphate was first applied in 1902.

The sequence of yields was broken at 1924, and the two sections 1897-1924 and 1925-1948 analysed separately. Figure 37 illustrates the course of yield after allowance has been made for variations in the seasonal rainfall. The first phase shows a marked increase in yield due mainly to the use of superphosphate and improved varieties such as Federation and Yandilla King, followed by a slight fall over the 10 year period terminating in 1924, while the second shows a linear increase at the rate of ½ bushel per acre per annum.

Cropping prior to 1897 had made phosphorus the limiting factor and reduced nitrogen reserves. As the phosphorus status was built up, consumption of nitrogen increased, and after 1915 it shows signs of becoming the limiting factor. Apart from re-arrangement of the rotations, the management has taken, since 1925, other important steps to improve the standard of farming. The total gain
of 15 bushels per acre over the second phase is partly due to these factors, principally higher-yielding varieties, but the increase in fertility attributable to the new cropping systems cannot be doubted.

Owing to the extreme difficulty of securing long and accurate records such as this, it is impossible to obtain confirmation of these results over a range of large-scale field conditions. The only data suitable for analysis are the reported results of rotation trials that have been conducted in Victoria and South Australia.

The observations used by Forster (1939) were derived from experiments laid down by the Department of Agriculture, Victoria, at three widely separated centres, Longerenong, Werribee, and Rutherglen. Rainfall at the experimental sites ranges from 15 to 23 in., and the soils, in the order given, are the typical Wimmera grey loam, a basaltic alluvium, and a grey-red buckshot silty loam, none of which had been seriously depleted by cropping prior to the initiation of the trials. Superphosphate was the only manural treatment applied to the plots. Yield of wheat from the rotation fallow-wheat, after adjustment for rainfall, was maintained at two centres, and increased at the third—Werribee. On the other hand, oat yields from the rotation fallow-wheat-oats declined markedly and significantly at the three places, indicating a definite reduction in fertility. The fact that wheat showed no evidence of this was probably attributable to the increased amounts of superphosphate and improved varieties that were incorporated from time to time in the trials. By differencing the yields of wheat from rotations involving one year's grazing and fallow only, Forster showed that yield from the former type of rotation was gaining significantly on the latter at Rutherglen and Werribee, but not at Longerenong. This would indicate that fertility was increased at the first two centres under the rotations used, since wheat yields were either maintained or increased at these places in the fallow-wheat rotation.

At Rutherglen, the responses to temporary sown pasture of the rotations was much greater than that obtained at Werribee and Longerenong, where the corresponding phase was a year's ley. Forster stated that other trials at Rutherglen in which pasture was ploughed in have shown a gain in fertility, thus demonstrating that with longer periods of pasture in the rotation, greater improvement in fertility can be expected.

Wark (1942), following the method outlined by Forster, analysed yield data from trials conducted at Booborowie, the Waite Agricultural Research Institute, and Roseworthy, in South Australia. The soil at the first two centres is a red brown earth, and at the third a loamy mallee, and seasonal rainfall is, in the order given, 14.4, 20.1, and 14.6 in. At the Waite Institute the trial was begun on virgin land, but the previous history of the experimental sites at the other two centres is not known definitely, though it is certain that cropping was conducted on each for some years.

The only data available at Roseworthy were yields derived from a fallow-wheat rotation under several manural treatments, and in each, yield declined significantly, even in the presence of ample supplies of superphosphate.
At Booborowie, wheat yields were maintained in the fallow-wheat rotation, but yields of stubble-sown oats and barley, from fallow-wheat-oats and fallow-wheat-barley rotations, respectively, declined strongly and significantly, showing as with Forster's data, a reduction of fertility. By differencing yields of wheat from rotations incorporating either one year of natural pasture or two years of ryegrass pasture, and from the rotation fallow-wheat, it was found that yield was maintained. Inclusion of one year of pasture also materially reduced the rate at which stubble-sown oats was declining.

With the addition of seven years' observations to the data studied by Wark, the yields from four rotations at the Waite Institute have been re-examined. The period covered by the new analysis is 1925-47 inclusive, and the rotations concerned are

1. fallow-wheat,
2. fallow-wheat-oats,
3. fallow-wheat-barley,
4. fallow-wheat-oats-pasture (Wimmera ryegrass),

in which all crops received a dressing of 187 lb. per acre superphosphate. Wheat yields declined in the first three rotations, and increased in the last, but owing to the excessive annual variation, none of these results was statistically significant, even after making allowance for fluctuations in seasonal rainfall.

When differences between yields of wheat in the series were taken, the following results were obtained:

<table>
<thead>
<tr>
<th>Difference of Wheat Yield</th>
<th>Regression Coefficient (bush./ac./an.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fallow-wheat-oats-pasture - fallow-wheat</td>
<td>0.27</td>
</tr>
<tr>
<td>fallow-wheat-oats-pasture - fallow-wheat-oats</td>
<td>0.58</td>
</tr>
<tr>
<td>fallow-wheat-oats-pasture - fallow-wheat-barley</td>
<td>0.28</td>
</tr>
</tbody>
</table>

but, as before, after adjusting for rainfall, annual variation still masks other effects, and only the second coefficient is significant, though the other two have the sign which was expected. The mean yields of wheat in the four rotations over the period were

<table>
<thead>
<tr>
<th>Rotation</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean yield (bush./ac.)</td>
<td>36.2</td>
<td>35.8</td>
<td>37.5</td>
<td>44.9</td>
</tr>
</tbody>
</table>

from which the superiority of the four-course rotation is evident, since the 7-9 bushel differences are very significant.

Finally, pending a more detailed analysis, a preliminary examination has been made of a rotational trial embodying a modern experimental design. The five rotations are
1. fallow-wheat,
2. fallow-wheat-peas-pasture (Wimmera ryegrass),
3. fallow-wheat-subterranean clover-pasture (Wimmera ryegrass),
4. fallow-wheat-oats-pasture (Wimmera ryegrass)
5. fallow-wheat-barley-pasture (Wimmera ryegrass).

All crops, including the pasture, received superphosphate at 2 cwt. per acre during 1937-41, but this was reduced to 1 cwt. per acre in subsequent years, since the phosphate supply had been built up during an interval prior to the beginning of the experiment. Half of each plot sown to a forage crop, namely, peas, clover, oats, and barley, was harvested each year and the produce removed, while the other half was grazed *in situ*. For present purposes, it is sufficient to quote the mean yields at the termination of the eighth year. These are set out in Table 5.

**Table 5**

<table>
<thead>
<tr>
<th>Rotation</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grazed</td>
<td>Harvested</td>
<td>Grazed</td>
<td>Harvested</td>
<td>Grazed</td>
<td>Harvested</td>
</tr>
<tr>
<td>Mean yields of wheat (bush./ac.)</td>
<td>43.49</td>
<td>41.59</td>
<td>37.41</td>
<td>34.32</td>
<td>39.77</td>
</tr>
<tr>
<td>Mean yields of forage crop total (air-dry) (cwt./ac.)</td>
<td>46.11</td>
<td>39.80</td>
<td>26.04</td>
<td>25.47</td>
<td>19.25</td>
</tr>
<tr>
<td>Mean yields of pasture (oven-dry) (cwt./ac.)</td>
<td>51.35</td>
<td>33.43</td>
<td>23.81</td>
<td>19.07</td>
<td>14.44</td>
</tr>
</tbody>
</table>

The yield of wheat from the fallow-wheat rotation is significantly lower than that of all four-course rotations, and there are significant differences among the latter, the most important being that the rotation including peas outyields the remainder. The pea crop is the outstanding forage, with a mean yield significantly greater than clover, oats, and barley. Two dry seasons, 1938 and 1940, greatly reduced the yield of subterranean clover as compared with peas, and this partly accounts for the large difference in the general means, but the mean yield of clover is significantly greater than that of barley or oats. Marked differences in the yield of temporary pasture in the various rotations have been evident throughout, and they have increased with time, all being significant. The effect of grazing is significant in the four cases.
Insufficient time has elapsed to show appreciable effects of the legumes on wheat yields in comparisons among the four-course rotations, but their superiority in other phases is clearly defined. The great advantage of peas compared with clover in this environment is also well established.

The high yields of wheat from the fallow-wheat rotation in this trial, 31.9 bushels per acre, and 36.2 bushels per acre in the one quoted above, are indicative of the ability of this particular soil type to withstand the strain of frequent cropping.

VI. ACKNOWLEDGMENTS

The work described in this paper was carried out as part of the research programme of the Section of Mathematical Statistics, C.S.I.R., and arose as the natural outcome of an investigation begun in collaboration with Dr. I. F. Phipps and Mr. A. T. Pugsley at the Waite Agricultural Research Institute, University of Adelaide.

The salient features of the history of the industry have been drawn from "The Centenary History of South Australia," Royal Geographical Society of Australasia, South Australian Branch, in particular Chapter 10, by Dr. A. E. V. Richardson, and acknowledgment is made to the Society for permission to use the block from which Figures 2-7 were prepared.

The author is indebted to the Director of Lands, South Australia, for a map showing the location of the wheat crop; the Chief and officers, Division of Soils, C.S.I.R., for information concerning the soils, and for a map giving the boundaries of the main soil groups; Messrs. F. Coleman and Sons of Saddleworth, South Australia, for permission to use the record of yield from their property; Misses E. M. G. Goodale and P. M. Ohlsson, and Messrs. R. Birtwistle and G. G. Coote, Section of Mathematical Statistics, C.S.I.R., for assistance in the assembly and preparation of the data for analysis; and to Mr. M. C. Childs, Division of Biochemistry and General Nutrition, C.S.I.R., for preparation of the majority of the figures. Finally, special acknowledgment is made to colleagues at the Waite Agricultural Research Institute and the Division of Biochemistry and General Nutrition, C.S.I.R., for placing unpublished data at the author's disposal, and to Mr. R. I. Herriot, Soil Conservator, Department of Agriculture, South Australia, for ready cooperation in making available his unrivalled knowledge of the wheat soils.

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