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THE CLIMATIC CONTROL OF AGRICULTURE IN SOUTH AUSTRALIA

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[Read April 8, 1937]

With Three Maps

Introduction

The climate of South Australia has been discussed by a number of workers, including Griffith Taylor (25), Adamson and Osborn (1), Trumble and Davies (29), Wood (30), Prescott (20), and Davidson (4), (5). It has been shown that the agricultural areas of this State are essentially dissimilar in climatic features from the more humid regions of Western Europe and New Zealand, in which an intensive type of agriculture is practised, and where major advances in pasture husbandry have occurred. Apart from differences in latitude, and, therefore, in the length of day and temperature range, all parts of the State are liable each year to a period of aridity which varies from several weeks in the lower south-east to more or less continuous drought in the desert regions of the north-west.

The nature and development of the agricultural flora appear to be governed principally by the seasonal relationship between length of day, rainfall, temperature and evaporation. The winter incidence of the rainfall coincides with a period of short days, moderate temperatures and low evaporation. The mean air temperature for the coldest month does not, at any centre, fall below 45° F. (16), and apart from the restricted area of elevated country, is above 50° F. Growth, therefore, although retarded in mid-winter (9), is not inhibited. The major "flush" with both cereals and pasture plants is in spring, when mean air temperatures in the neighbourhood of 60° F. (15·5° C.) coincide with conditions of surplus moisture. From spring or early summer until autumn, the duration of this period depending on the location and the season, growth tends to be limited by associated conditions of low rainfall and high evaporation.

Length of Day and Temperature

The length of day and the mean air temperature do not vary greatly from centre to centre within the agricultural areas. The latter lie between the parallels of 32° S., and 38° S.; elevation varies from sea level to approximately 2,000 feet, and the mean air temperature for the coldest month varies from 45·5° F. at Stirling West to 52·5° F. at Kingscote. On the other hand, both length of day and temperature act as decisive factors in determining the nature of the crop and pasture types that can be grown within this region. The importance of these factors in regard to varietal adaptation in wheat has been demonstrated by Forster *et al.* (11) and Forster and Vasey (12). At the Waite Institute it has been observed that herbage plants from European and North American sources may fail to flower and set seed normally, although supplied with abundant artificial water. Examples are *Phalaris arundinacea, Avena elatior, Agropyron tenerum, Bromus inermis.* This is also true of ecotypes or varieties of *Lolium perenne, Dactylis glomerata, Phleum pratense* and cereals from northern European sources. On the other hand, types from southern Australia, when grown in Great Britain, usually run to stem and seed rapidly, with comparatively little vegetative growth (13), (11).

The majority of the naturalized herbage plants that have spread with rapidity over the agricultural areas of South Australia are of southern European, Asiatic or Mediterranean origin. Similarly, the cultivated herbage plants of importance, namely subterranean clover, lucerne, Wimmera rye-grass, *Phalaris tuberosa* and the types of perennial rye-grass most suited to local conditions appear to have originated under climatic conditions approaching the Mediterranean type.

The optimum range of temperature for the germination of winter-grown herbage plants has been found by the author (27) to lie between 10° C. and 28° C. (50-82° F.). On the other hand, sub-tropical species which can be grown at Adelaide only by the aid of summer irrigation, are characterised by the range 22-38° C. (72-100° F.). The mean monthly soil temperature at one inch, at the Waite Institute for the period 1925-35, falls within the former range over the period April to November, inclusive, and within the latter range over the period November to March, inclusive. It will be shown later that the period April to early November coincides with the mean effective rain period at this centre; from November to the end of March average conditions of summer aridity prevail.

Rainfall

In Australia, generally, the mean annual rainfall has been most frequently employed as a climatic index for agricultural purposes. That the incidence, reliability and effectiveness of the rainfall are of considerable importance has been generally recognised, although in the past there has been an absence of satisfactory measures of these factors. The realisation that wheat production is largely governed by the rain falling during the growing period of the crop, has led to the somewhat arbitrary choice of the April-October or April-November rainfall as a measure of the seasonal precipitation (23), (19). In this particular State, "Goyder's Line" (18) has been largely used as a guide to agricultural settlement. This line was based on the appearance of the country following two years of severe drought in 1864 and 1865, and was also related to the southern limits of saltbush steppe. No definition of the line has been found possible in terms of rainfall, and it was not originally associated with wheat production, but it has been consistently employed as a guide to the limits of agricultural settlement and as a basis for assessing the suitability of the conditions for wheat culture. Experience has shown that it has proved, with a few exceptions, a fairly reliable guide for this purpose.

That the mean annual rainfall itself is an unsatisfactory guide to local climatic variation is indicated by the fact that areas in the south-eastern portion with only 19 inches of rainfall are by common acceptance more humid than centres only 3 degrees farther north which receive 20 to 24 inches.

Few attempts have been made to differentiate the effects of rain falling at different periods of the year, but in this connection Trumble and Cornish (28) recently showed that the yield of a natural pasture in the Adelaide environment was largely governed by autumnal and early winter rainfall. The spring rains, which had been popularly believed to be of major importance in determining the total seasonal yield, were found to have little effect.

It has also been shown by Cornish (3) that over a period of 95 years at Adelaide, there has been a definite oscillation, with a period of 23 years and an amplitude of 30 days, in the incidence and duration of the winter rains. The total quantity precipitated showed no statistically significant changes.

Evaporation and Saturation Deficiency in Relation to Effective Soil Moisture

Until recently, evaporation has not received the attention it merits as a factor governing the effectiveness of rainfall. This is in part due to the practical difficulties associated with its measurement and a lack of standardization among the types of evaporimeters in use. A satisfactory approach to the question of effective soil moisture has been made possible, however, by the use of saturation deficiency and its relation to rainfall as expressed by the Meyer ratio.

Prescott (20), (21) reviewed the various methods that had previously been designed to secure a single numerical index to climatic conditions, and adopted the Meyer ratio of rainfall to saturation deficiency in connection with the leaching factor of soils and the classification of soil and vegetation. More recently (22) he related the monthly Meyer ratio of 4 or 5 to the distribution of the Australian deserts. Davidson (4) showed that for South Australia the mean monthly values for saturation deficiency at different stations could be expressed in terms of evaporation by referring these values to the data for free water surface evaporation at Adelaide. By this means it was possible to define the months and approximate areas in which the mean monthly rainfall exceeded evaporation. He also applied this method to the remaining States of the Commonwealth (6), (7), using evaporation factors of 1·0 and 0·5, and recently mapped Australia in terms of bioclimatic zones (8), using a ratio of rainfall to evaporation equal to 0·5, as a critical monthly value.

The Evaporation of Water from a Standard Tank

The mean monthly evaporation from a standard 36″ tank [1] and the mean monthly rainfall for the period 1925-35 at the Waite Institute, together with the standard deviations of the mean values, are shown in Table I. It will be seen that evaporation has been materially less variable than the rainfall.

Table I

Showing the mean monthly rainfall and evaporation (from a standard 36″ tank) at the Waite Institute, Glen Osmond, 1925-35. (Inches.)

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1. Rainfall:													
Mean	·59	·98	1·03	1·68	3·20	3·12	3·10	3·32	2·98	1·80	1·11	1·06	23·98
Standard Error	±·11	±·33	±·25	±·41	±·64	±·48	±·30	±·37	±·30	±·31	±·28	±·32	±·68
S.E. %	18·9	33·2	24·4	24·6	20·0	15·4	9·8	11·0	10·1	17·3	26·0	30·8	2·8
2. Evaporation:													
Mean	9·23	7·40	6·79	4·22	3·04	1·95	1·93	2·50	3·37	4·83	6·71	8·49	60·47
Standard Error	±·36	±·25	±·17	±·23	±·14	±·10	±·09	±·09	±·10	±·13	±·12	±·21	±1·1
S.E. %	4·0	3·4	2·6	5·5	4·7	5·0	4·6	3·6	3·0	2·8	1·8	2·5	1·9

Although the mean variability of the total yearly rainfall is only 2·8 per cent., the variability of the monthly values ranges from 10 to 33 per cent. The variability of the annual evaporation figure is again low, 1·9 per cent., but here the monthly values are also low, the standard error ranging from 1·8 to 5;5 per cent.

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(1) The standard evaporimeter consists of an inner circular tank 36″ in diameter and 36″ in depth, surrounded by an outer jacket 48″ in diameter and 34″ in depth. The water in the jacket is maintained at the same level as in the tank, and the flange of the tank is thus two inches higher above water level than the outer rim of the jacket.

The mean rate at which water is lost from the evaporimeter following individual falls of rain also tends to be comparatively uniform, as shown in Table II. A fall of rain has been taken as the rain falling on three or less consecutive days and has been related to the time taken for this rain to be dissipated by evaporation from a 36″ tank, commencing from the day following the initial recording of the fall.

Table II

Showing the mean rate at which rainfall was evaporated from a free water surface (36″ tank), Waite Institute, 1925-35.

$y = a + bx.$

(y = time in days for x = rainfall to be evaporated)

Month -	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Constants												
a	·75	·37	·25	·66	−·44	·20	·95	·77	·15	0	·41	·56
b	·043	·046	·055	·083	·145	·166	·154	·116	·094	·077	·048	·036
S.E. (b)	·0061	·0041	·0041	·0071	·0055	·0045	·0057	·0052	·0036	·0027	·0023	·0015
$\tan^{-1} b$	2·5°	2·7°	3·2°	4·7°	8·3°	9·4°	8·8°	6·3°	5·4°	4·4°	2·8°	2·1°
Days taken for one inch to be evaporated.	5·0	5·0	5·7	9·0	14·1	16·8	16·4	12·4	9·6	7·7	5·2	4·2
S.E. $\bar{y}$ (%)	4·95	6·02	4·78	4·76	3·68	3·01	2·61	3·31	3·16	3·42	4·98	3·59

Adverting to Table I, it will be seen that the mean rainfall for each of the five months, November to March, inclusive, is below 1·20 inches. Over the eleven years in question, 76 separate falls of more than 10 points occurred in these months, but only eight of them exceeded one inch. Thus, at the Waite Institute, rain received in the five months' period from November 1 to March 31 is, in most cases, lost from a free water surface within five days and can have little effect in promoting and sustaining the growth of herbage plants.

The Evaporation of Water from Soil

The rate of evaporation from soils has received attention from Keen (14), Fisher (10) and others, but principally under laboratory conditions. The results of this work have shown that both the external environment and the internal properties of the soil, which may be suitably expressed in terms of the moisture equivalent, govern the rate of evaporation from a soil. The latter can be expressed, in the case of drying chambers, by means of linear and discontinuous rate curves, provided that movement of moisture through the drying mass is uniform. It is generally agreed that so long as the soil surface remains saturated, the rate of evaporation approximates that from a free water surface maintained under identical external conditions. As the surface soil dries, however, retentive forces depending on moisture equivalent and the amount of moisture present come into play, causing a reduction in the evaporation rate.

To investigate the relative losses by evaporation from the soil surface compared with that lost from free water, soil blocks, 14·4 cm. x 11·4 cm. x 15 cm. in depth, were removed *in situ* from the experimental field at the Waite Institute and fitted to glass containers of similar size (capacity, 2·4 litres), each jar being covered with bible paper. Corresponding jars were filled with water, in all cases the surface level being 2 mm. from the edges of the jars. Tests were carried out in quadruplicate in March, April and May, 1936, the equivalents of 0·20, 0·40 and 0·60 inches of rain being applied to the soil blocks when at the hygroscopic coefficient. The jars were maintained in a glass house enclosure, with glass roof and open sides, and were weighed three times daily. The evaporation from a standard evaporimeter alongside the tests was found to be materially less than that from the jars containing free water. This was due to differences in the height of the protecting flange, and in the volume and surface area of the water, resulting in turbulence differences.

The depth to which the surface soil was wetted by varying applications of water under laboratory conditions of low evaporation was tested separately and found to be as follows:—

Depth of Penetration	Rainfall Equivalent of Water Added.				
	0·20″	0·40″	0·60″	0·80″	1·00″
Immediately after application	0·8″	1·5″	2·1″	2·7″	3·4″
After 20 hours	1·5″	3·1″	3·6″	4·6″	5·3″
Increase in penetration	0·7″	1·6″	1·5″	1·9″	1·9″

The minimum effective amount of rain in a single fall has been discussed in a footnote by Davidson (8), p. 91. Falls of 0·15, 0·20 and 0·25 inches have been suggested by various workers, and Osborn, Wood and Paltridge (Proc. Linn Soc. N.S.W., **vol. lvi.**, p. 302, 1936) have stated that falls lighter than 0·25 inches do not penetrate the soil more than 2-3 cm. On the basis of the present observations, 0·25 inches would penetrate the Waite Institute soil to one inch (2·5 cm.) immediately, and after 20 hours of low evaporation would be expected to reach a depth of 1·9 inches (4·8 cm.). A fall of ·20 inches, by penetrating 0·8 to 1·5 inches (2·0 to 3·8 cm.) would be regarded as effective, provided it were followed by conditions of low evaporation.

The results of ten independent determinations of the loss from soil of applications equivalent to 20, 40 and 60 points of rain have been expressed as a ratio of the water added to the water lost by evaporation from a free water surface during the period taken for the wetted soil to be reduced to the wilting point, and are given in Table III.

TABLE III

Comparison of soil evaporation with free water surface evaporation, following varying applications of moisture, Waite Institute, March-May, 1936.

Date Test commenced.	Water added = R (inches).	Days taken for added water to evaporate to wilting point.	Evaporimeter loss = E′, for same period (inches).	Mean loss by evaporation = E″, from jars for same period (inches).	Ratio R/E′	Ratio R/E″
28th March	·20	2·3	·426	·724	·47	·28
	·40	5·3	1·096	1·791	·36	·22
	·60	7·5	1·471	2·265	·41	·26
4th April	·20	4·0	·742	·880	·27	·23
	·40	4·2	·762	·901	·52	·44
	·60	14·0	2·140	2·906	·28	·21
16th April	·20	7·2	·732	·800	·27	·25
	·40	12·0	1·394	1·745	·29	·23
	·60	18·0	2·212	2·983	·27	·20
4th May	·20	5·5	·726	·911	·28	·22
				Mean	·34 ± ·029	·25 ± ·022

The observations covered a period in which the mean rate of evaporation (evaporimeter reading) for the duration of any single test varied from ·102″ to ·207″ per day; that is to say, at rates which normally occur at the Waite Institute in the months of March, April, May, September, October, November. By means of a more extensive series of tests, it would be possible to establish a relationship between soil evaporation and free water surface evaporation for all rates of the latter and for different types of soil.

The present results may be expected to hold for the commencement and termination of the growing season at the Waite Institute, and indicate that under these conditions the surface will be maintained at or above the wilting point when the rainfall over a period of weeks is approximately one-third the evaporation from a 36″ tank. The value 0·3E (or $\frac{E}{3}$) is taken, for simplicity in handling large numbers of readings.

Length of the Growing Season

The concept of the growing season, as delineated by low temperature or moisture deficiency, has been in evidence for many years and, in the older agricultural countries, much attention has been paid to the limitations imposed by temperature. Blackman (2), for instance, has recently shown under English conditions that below a soil temperature at 4 inches of approximately 42° F. no growth of pasture takes place. In South Australia this temperature, as previously indicated, is exceeded for the greater portion of the coldest month, in all parts of the State.

The periods over which the mean air temperature remained above 50° F. and 68° F. were employed by Köppen (15) to define the tropical, sub-tropical, temperate, cold and polar belts, as early as 1900. Schimper (24) employed the isotherm of 43° F. for the coldest month to mark the boundary between deciduous and evergreen forest, and Miller (17) used this figure to show, graphically, the length of the growing season.

In Australia, generally, the growing season for pasture commences when the moisture gained by the soil from rainfall is sufficiently greater than the soil evaporation to initiate and sustain the vegetative growth of herbage plants; it concludes when transpiration has exhausted the available reserves of moisture held by the soil and the rate of soil evaporation has again exceeded the rate at which rain is received, as measured over a suitable interval of time, *e.g.*, per month or per fortnight. The period over which available moisture tends to occur in the surface layers of soil is very clearly defined in the Mediterranean type of climate; it varies in length with the season and with the locality.

In connection with the use of the factors, evaporation or saturation deficiency, for the determination of this period, the following two questions arise: (1) What expression of the free water surface evaporation should be taken to represent soil evaporation? (2) Can a finer measure of the growing period than a number of whole months be obtained?

So far as the first is concerned, the data in Table III indicate a value in the neighbourhood of 0·3E for the Waite Institute soil, and further justification for the selection of this factor will be shown. Assuming for the moment that 0·3E is satisfactory, it is apparent, in regard to the second question, that an interval of almost one or almost two months shorter than the true period is likely to be recorded where 0·3E is slightly in excess of P for one or for two months, respectively, at the commencement and/or termination of the rain period.

The interval between the two points at which the line for P crosses the line for $0\cdot\dot{3}E$ can be readily measured, however, for if P', P'' and E', E'' are the respective rainfall and evaporation values for the two adjoining months showing an inversion of P with respect to $0\cdot\dot{3}E$, then the point at which the line for P crosses the line for $0\cdot\dot{3}E$ is given by the ratio

$$\frac{P'' - 0\cdot\dot{3}E''}{(0\cdot\dot{3}E' - P') + (P'' - 0\cdot\dot{3}E'')}.$$

Under South Australian conditions the cross-over is comparatively steep, but the use of functions varying from 0·2E to 0·6E gives values ranging from 6·1 months to 8·5 months at the Waite Institute, as shown in Table IV.

TABLE IV

Showing the period over which the mean monthly rainfall exceeded (1) the mean monthly evaporation from a 36″ tank, (2) various expressions of the latter value, Waite Institute, 1925-35.

Coefficient of E.	Commencement.	Completion.	Interval (months),
1·0	29th April	20th Sept.	4·7
0·6	12th April	14th Oct.	6·1
0·5	7th April	21st Oct.	6·5
0·4	1st April	28th Oct.	6·9
$0\cdot\dot{3}$	27th March	5th Nov.	7·3
0·3	23rd March	8th Nov.	7·6
0·2	10th March	23rd Nov.	8·5

The work of Trumble and Cornish (28) indicated that over this period of years, rain falling in April was more effective in determining the total yield of a natural pasture at the Waite Institute than in any other month, but that the March rainfall was highly effective in certain seasons. Moreover, the termination of seasonal growth invariably occurred about the first week in November. This suggests that a value of 0·3 E or $0\cdot\dot{3}$ E would be suitable, especially as effective rains in March would be most likely to fall towards the end of the month.

A more rigid test was made by determining the length of the growing season for natural pasture for each of the eleven years at the Waite Institute, using $0\cdot\dot{3}E$, both, directly from the monthly evaporation readings and indirectly from the monthly value for saturation deficiency; these were then compared with the estimated length of the growing season for each year, determined independently by inspection of the daily rainfall and evaporation records, referred to the data given in Table II, and collated to field observation. The results are given in the following table:—

TABLE V

Length of growing season for natural pasture at the Waite Institute for each of the years 1925-35 as determined from (1) monthly rainfall and evaporation, (2) monthly rainfall and saturation deficiency, (3) estimated from daily records collated to field observations.

Year	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	Mean
(1) Evaporimeter	6.87	7.23	5.78	7.33	6.17	6.34	6.57	8.24	7.20	8.79	8.67	7.20
(2) Sat. Def.	6.84	7.68	5.62	7.11	6.03	6.12	6.49	8.14	6.93	8.63	8.41	7.09
(3) Estimated	6.90	6.89	5.61	7.76	5.98	6.54	6.84	8.00	6.93	8.21	8.31	7.09

Mean Length of Growing Season

1.	Mean break to mean close (estimated) .... 3rd April to 5th November	7·09 months
2.	From mean rainfall and mean evaporation for 11 years 27th March to 5th November	7·33 months
3.	Mean of 11 yearly values determined from evaporation 2nd April to 4th November	7·09 months
4.	Mean of 11 yearly values determined from saturation deficiency .... 31st March to 5th November	7·20 months

The results show good agreement, the greatest deviation in any individual year being ·65 of a month, or 20 days, whereas most of the differences are of a few days only, and the four eleven-year means are particularly close.

The Evaporimeter Factor

The factors 1·0 and 0·5 have been employed by Davidson (7) to correlate the number of months in which the P/E ratio exceeds one or other value with the distribution and seasonal fluctuations of insects affected by moisture conditions at the soil surface. In the course of the present investigations a comparison was made between the Adelaide and Waite Institute evaporimeters, since Davidson's South Australian values for evaporation were based on the Adelaide tank. The following results were obtained:—

Mean Free Water Surface Evaporation

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Waite Institute (1925-35)	9.23	7.40	6.79	4.22	3.04	1.96	1.93	2.50	3.37	4.83	6.71	8.49	60.47
Adelaide (65 years)[2]	9.08	7.39	5.92	3.50	2.05	1.26	1.29	1.88	2.87	4.78	6.61	8.49	55.12
Adelaide (with Waite Institute as 100)	98	100	87	83	67	64	67	75	85	99	99	100	91

The progressive reduction of the value for Adelaide, compared with the corresponding Waite Institute value, from 100 in February to 62 in July, followed by a progressive rise to approximately 100 for the entire period October to February, led to a detailed inspection of the Adelaide evaporimeter. This revealed differences in its shape and size and the type of screen, compared with the standard equipment at the Waite Institute. The evaporimeter at Adelaide, moreover, is temporarily shaded by a neighbouring building during the early afternoon, in the winter months. The building in question is the observatory, and it was erected prior to the installation of the evaporimeter. A comparison of the saturation deficiency: evaporation relationships at the two centres shows that the use of the factor 0·5 in conjunction with the Adelaide evaporimeter corresponds to a factor of 0·31 ± ·015 for the Waite Institute evaporimeter over the period March-November. Owing to the steepness of cross-over of the rainfall and evaporation curves in South Australia, the use of the factor 0·5 for Adelaide evaporation data and $0 \cdot \dot{3}$ for Waite Institute evaporation data give, under South Australian conditions, similar values when used to determine the period over which moisture tends to be available in the surface soil. It is a coincidence that Davidson's factor of 0·5 should fit these results so closely when applied to the Adelaide readings, but this figure is too high to give a true value for the agricultural rainfall season, when assessed from 36″ standard tank readings, under fully exposed conditions.

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(2) From the Official Year Book of the Commonwealth of Australia, No. 28 (1935).

The ratio $P/E = 0\cdot\dot{3}$ in the case of the standard exposed 36″ tank, or $P/E = 0\cdot5$ for the Adelaide evaporimeter, gives under South Australian conditions a measure of the mean time interval over which rainfall influences the growth of annual herbage plants; this is the period over which the soil tends to be maintained at or above the wilting point. The Meyer ratio of $P/S.D. = 5$ may be used similarly (23). This interval may be referred to as the period of influential rainfall, or the influential rain period. It provides a measure of the effective rain-

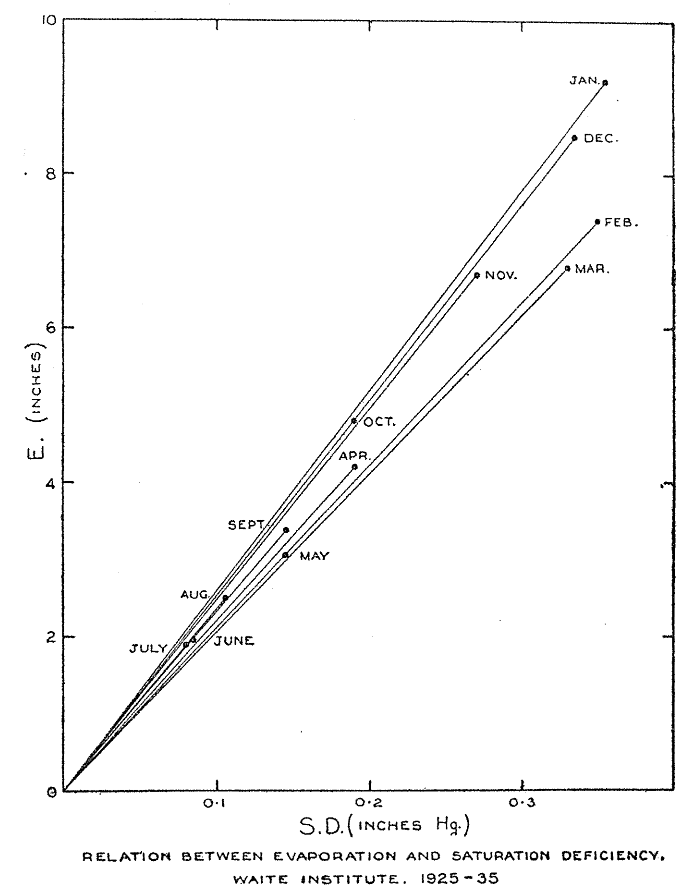

Fig. 1
Relation between the mean monthly free water evaporation from a standard 36″ tank and mean monthly saturation deficiency, Waite Institute, 1925-35.

fall season, but does not necessarily coincide with the full growing season in the case of plants able to use subsoil reserves of moisture.

For survey purposes, either free water evaporation or saturation deficiency may be used. Szymkiewicz, quoted by Prescott (21), pointed out that saturation deficiency was more satisfactory than evaporation owing to the dependence of the latter on the form of the evaporimeter, as well as on humidity, atmospheric pressure, wind velocity and insolation. Provided that evaporation is measured from a standard tank under standard conditions, however, it has the advantage of providing a full record over each 24 hours, as against the single 9 a.m. reading for wet and dry bulb temperature; moreover, it is the closest single measure of the atmospheric conditions affecting transpiration or soil evaporation, and it expresses water loss in the same unit as the rainfall figure expresses water gain.

The relationship between the mean monthly evaporation and the mean monthly saturation deficit for a period of eleven seasons at the Waite Institute is shown in fig. 1. The relation is closer than that obtained by Davidson (4) in the case of the Adelaide evaporimeter, for a period of 60 seasons. The divergence between the values for October-January and those for February-May is due to a variable wind factor. Allowing for this factor the relation becomes more closely linear.

Duration of Rainfall Season in South Australia

Using the mean monthly rainfall data for 206 stations and the estimated evaporation for these stations, determined from maps drawn for each month on the basis of saturation deficiency for 25 stations, the duration of the period of influential rainfall over the agricultural areas was determined and a map prepared (Map I) on which these data were related to the main types of climax vegetation and the distribution of wheat and seeded pasture at the commencement and close of the five-year period of 1929-34. This period, commencing with the highest peak of wheat production in 1929, and concluding with the latest returns available when the map was prepared, was characterised by a material decrease in the area sown to wheat and a substantial increase in the area seeded to permanent pasture. Owing to the critical economic conditions for wheat production over this interval of time, it is to be expected that the reductions in acreage will have occurred in those areas least suitable for wheat production.

Relation between Agricultural Development and Length of the Rainfall Season

The isochrones shown on Map I are for 5·0, 6·0, 7·5 and 9·0 months, respectively. Each of these lines appears to possess material significance. It will be observed that the 5 months line corresponds closely to the outer limits of wheat cultivation apart from a small area between this line and the Murray River, which is of some interest. The 5 months line also gives a close expression of Goyder's line, at least for those portions of Goyder's line where the latter fits closely to the present limits of wheat distribution. Where the two lines diverge, the 5 months line is in better agreement.

The presence of the Murray River in the dry eastern portion of the State has influenced the extension of the wheat area outside the 5 months isochrone. The river existed as a highway, with towns established along its course, many years before the country south of it was opened to settlement by the construction of railways and roads. It was natural, therefore, that the destination and termination of the latter should be the river. Had no waterway existed, it is probable that the northernmost limits of wheat cultivation would have little exceeded the 5 months line, as is the case in the remaining parts of the State.

The average duration of the five months period in South Australia is May to September, inclusive, but individual seasons may range from March-July to July-November, in addition to the scatter of seasons with a period longer or shorter than five months.

Seeding, if properly carried out, commences after the opening of the rainfall season, and the seeding operations of an ordinary wheat farm take a fortnight or more to complete. Furthermore, a period of ten days or longer elapses between sowing and the appearance of the crop above ground. Thus the full crop would not appear until at least a month after the commencement of the rainfall season.

At the Waite Institute,(3) the earliest wheats require four months from brairding to heading, and six months from brairding to maturity when sown in May. They require two-and-a-half months to heading and four months to maturity when sown in July. Under these conditions, therefore, soil growing wheat should contain available moisture for five months after the commencement of the rainfall season, to ensure full maturity of the grain. The earliest wheats have not in any season, at the Waite Institute, matured their grain prior to mid-November.

In the more northerly wheat areas, ripening would tend to occur several weeks sooner owing to slightly higher temperatures and accelerated transpiration during the ripening period. It is known in practice, for instance, that the wheat harvest in the earlier districts frequently commences in mid-October. An essential feature of the five months period is that its termination occurs, on the average, at the end of October, but frequently earlier. Provided sufficient moisture is held in the subsoil to satisfy transpiration requirements in the final stages, the wheat plant is capable of continuing its growth for several weeks following the termination of the rainfall season. The vicinity of the five months isochrone is characterised, however, by low rainfall within the rainfall season, absence of subsoil retentiveness associated with limestone to a considerable degree, and a high variability of seasonal rainfall conditions. To ensure even moderate yields of grain, therefore, an influential rain period of five months or longer appears to be required.

Perkins (19) recently determined the mean wheat yield for each hundred in South Australia for the 20 years period, 1915-35. Relating Perkins' data to the length of the rain period, as here determined, the following results are obtained:—

TABLE VI

Showing mean yield of wheat per hundred (1915-35), according to the length of the rainfall season in South Australia.

	Period (in months)			
	$< 5 \cdot 0$	$5 \cdot 0$ to $6 \cdot 0$	$6 \cdot 0$ to $7 \cdot 5$	$> 7 \cdot 5$
1. MURRAY MALLEE—				
No. of hundreds	47	22	14	—
mean of hundred means (bush.)	5·33	7·16	6·72	—
No. of hundreds > 6·0 bush.	16	15	10	—
No. of hundreds > 9·0 bush.	—	6	1	—
2. CENTRAL AREAS—				
No. of hundreds	39	36	74	12
mean of hundred means (bush.)	5·39	11·05	15·71	14·28
No. of hundreds > 6·0 bush.	11	35	74	12
No. of hundreds > 9·0 bush.	—	25	74	12
3. WEST COAST—				
No. of hundreds	41	74	37	7
mean of hundred means (bush.)	4·83	6·39	7·92	9·09
No. of hundreds > 6·0 bush.	3	38	27	6
No. of hundreds > 9·0 bush.	—	6	11	3
4. STATE (excluding South-East)				
No. of hundreds	127	132	125	19
mean of hundred means (bush.)	5·18	7·80	12·39	12·36
No. of hundreds > 6·0 bush.	30	88	111	18
No. of hundreds > 9·0 bush.	—	37	86	15

(3) The author is indebted to Dr. I. F. Phipps for information concerning the dates of flowering and maturity of wheat varieties grown at the Waite Institute.

There is a major distinction between the soils of the central areas on the one hand and most of the West Coast and the Murray Mallee soils on the other. The soils of the central areas, associated with the Mount Lofty and Flinders Ranges, are largely of the red-brown earth or the grey soil type, and overlie retentive subsoils. These show a marked increase in yield with a lengthening rainfall season up to the 7·5 months line, after which with increased leaching the soils tend towards the podsolic type and yields are low except in small local areas of more productive soils. Where the influential rain period is less than five months, however, the yields for the most part fall below the economic limit given by Perkins, namely 6·0 bushels per acre. In the mallee areas, both on the West Coast and in the Murray Mallee, the yields are still lower than those of the central areas, where the rain period is less than five months; as this period lengthens, the yield increases, but not greatly. The soils in these areas are of the light mallee type, and in many cases overlie limestone rock; retentivity is not a common feature.

In view of Perkins' figure of 6·0 bushels per acre, the 5·0 months isochrone would appear to be a satisfactory delineator of the outer limit to economic cereal culture under all soil conditions in South Australia. This line is materially south of the 10″ annual isohyet.

Relation between Pasture Development and Length of the Rainfall Season

Adverting to pasture establishment, the area under permanent seeded pasture in 1929 and 1934 is also shown on Map I. It will be seen that apart from those areas north of Adelaide, seeded pasture lies entirely within or close to the 7·5 months isochrone. This line appears to be critical in relation to subterranean clover, on which the pastures south of Adelaide are largely based. This plant is a surface-rooting, annual mesophyte, dependent on surface conditions of moisture supply. It is at its best on light or friable surface soils, with a retentive clay subsoil within nine inches or less of the surface level. At the Waite Institute the commercial mid-season type grew satisfactorily but failed to re-seed in each of the years 1925, 1926, 1927, 1928 and 1929, after which attempts to cultivate it were abandoned, and the Dwalganup variety which flowers four to six weeks earlier, was grown with success and is now established over much of the property. The highest value for these five seasons, based on evaporimeter readings (Table V) was 7·3 months in 1928. In two later seasons, 1934 and 1935, with influential rain periods of 8·8 and 8·7 months, respectively, the mid-season strain produced seed abundantly. The mean influential rain period for the Waite Institute meteorological station is 7·1 to 7·3 months. On the higher slopes of the property, as the value of approximately 7·5 months is reached and exceeded, the clover is to be found in significant quantities, growing naturally. The close fit of this line to the known limits of the clover over the Mount Lofty Ranges, Kangaroo Island and the upper South-East is very striking. It appears perfectly safe to mark the limits of the mid-season strain by the 7·5 months line. The earlier maturing strain has been grown successfully over a period of five years, at centres with mean values of 6·5 to 7·5 months, and can probably be adopted as an improved pasture species at least to the 6·5 months line, and possibly to the 6·0 months line.

The 9·0 months line shows a close agreement with the limits to the natural distribution of such plants as *Poa pratensis, Dactylis glomerata, Agrostis stolonifera, Holcus lanatus* and *Trifolium repens*. These have not persisted except when the mean influential rain period exceeds nine months, or where additional soil moisture is available in summer. *Lolium perenne* and *Trifolium fragiferum* are found almost to the 7·5 months line, depending to a great extent on soil fertility or soil type.

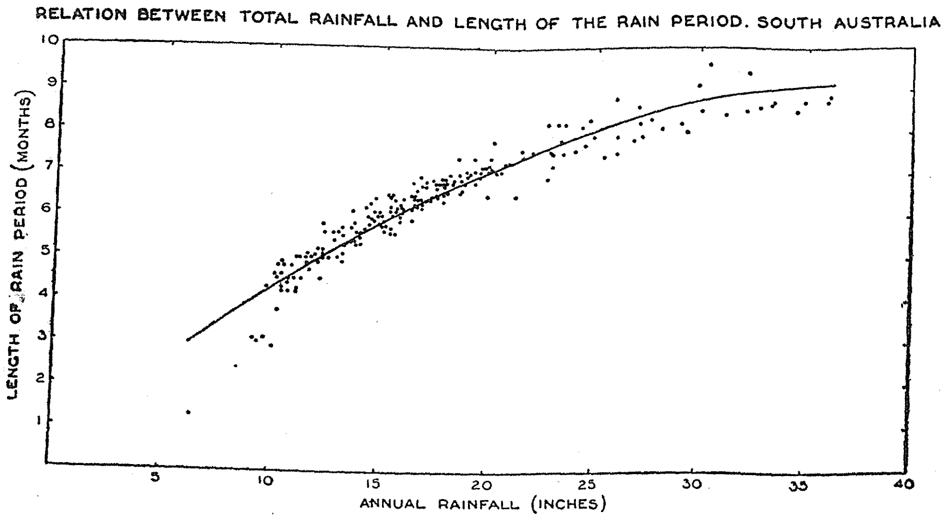

Fig. 2
Graph showing relation between mean annual rainfall and length of the mean influential rain period in South Australia.

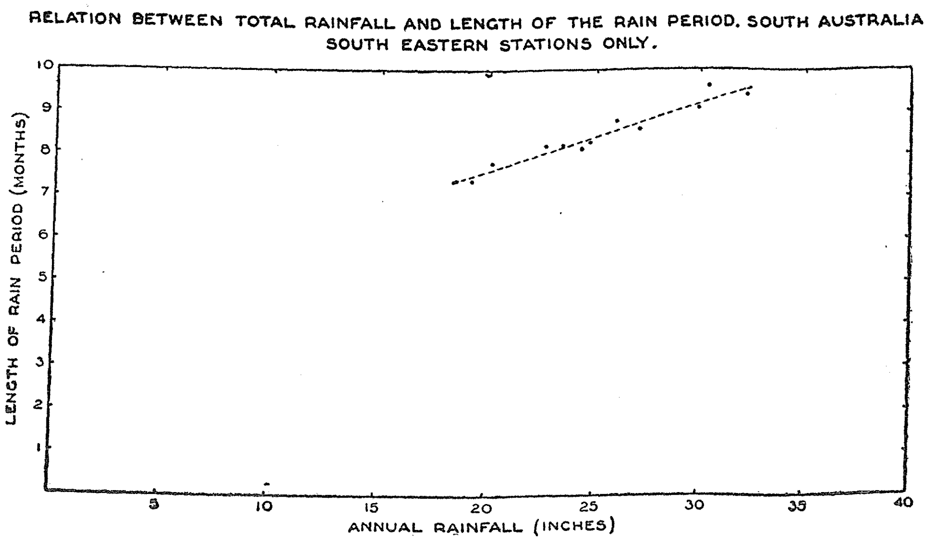

Fig. 3
Relation between annual rainfall and influential rain period, South-eastern stations only.

There is a general relationship between the mean annual rainfall and the influential rain period, and this is shown in figs. 2, 4. The curves have been fitted to the data for (1) the entire State, (2) Mount Lofty Range stations receiving more than 20 inches, and (3) South-Eastern stations receiving more than 20 inches. The points of particular interest are, firstly, the marked difference between the length of the influential rain period in relation to total rainfall, as between the elevated stations on the one hand and the South-Eastern stations on the other; and secondly, the marked deviation from the general curve of the stations receiving less than 10 inches. This deviation indicates a change in the rainfall type, due to the replacement of the Antarctic influence as a dominant causal factor, by sporadic monsoonal disturbances; and it appears to justify the use of the 10″ annual isohyet as a border line between the "Mediterranean" and "arid" environments in South Australia. So far as the higher rainfall areas in the Mount Lofty Ranges and the South-East are concerned, the difference between the two zones explains why subterranean clover requires a mean annual rainfall of 24 inches in the Mount Lofty Ranges and only 19 inches in the South-East, the mean influential rain period of 7·5 months being the determining factor in each case.

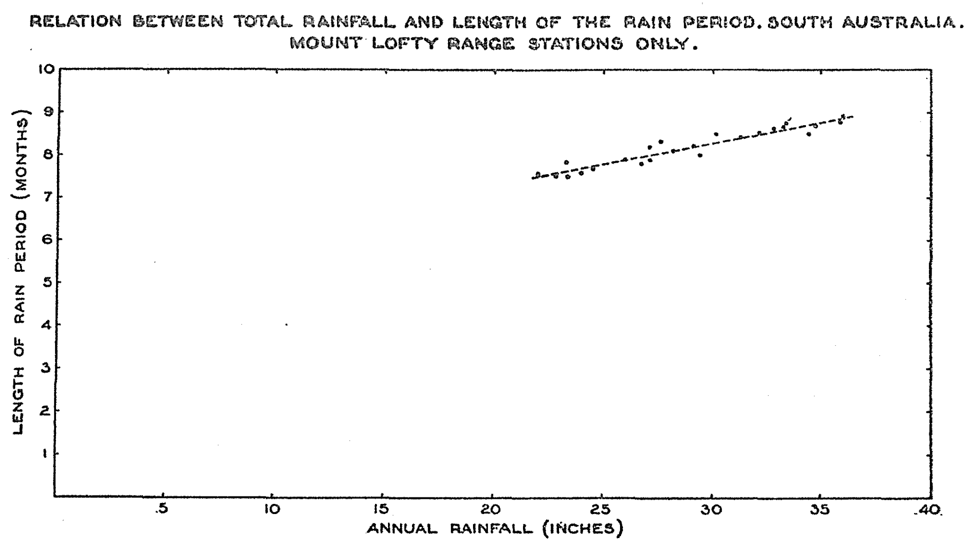

Fig. 4
Relation between annual rainfall and influential rain period,
Mount Lofty Range stations only.

Linked with the length of the influential rain period and its converse, the period of summer aridity, is the intensity of the latter. Thus a 9·0 months period of influential rainfall is characterised, not only by a shorter summer but by a cooler and more humid summer than a 7·5 months period.

Influential Rainfall

Having obtained a measure of the seasonal rain period, it is now possible to determine the seasonal rainfall, or influential rainfall, on a logical basis, instead of empirically. Since the period of influential rain defines the interval during which the soil may be expected, under average conditions, to remain above the wilting point, there is justification for taking the rain falling within this period as influential rain and discarding the rain falling outside the period as being ineffective, at least as regards annual herbage plants. Very occasionally, in this type of environment, a liberal summer rain may promote the development of a little herbage from perennial species, but such rains are infrequent, sporadic and invariably followed by high evaporation, resulting in the rapid dissipation of moisture. There appears to be no justification, therefore, for including any measure of these rains as a normal seasonal feature. The use of a correction factor for evaporation over the influential rain period, moreover, appears to be unnecessary, since the effectiveness of the rain in terms of the growth rate of plants increases, within limits, as temperature and evaporation become greater. The influential rainfall is taken, therefore, as the total quantity of rain falling within the influential rain period.

This quantity has been determined for each of 206 stations and is shown, for South Australia, on Map II. As is to be expected, the isohyets differ considerably from the April-November isohyets (19), which are commonly taken to indicate the rain received during the growing period.

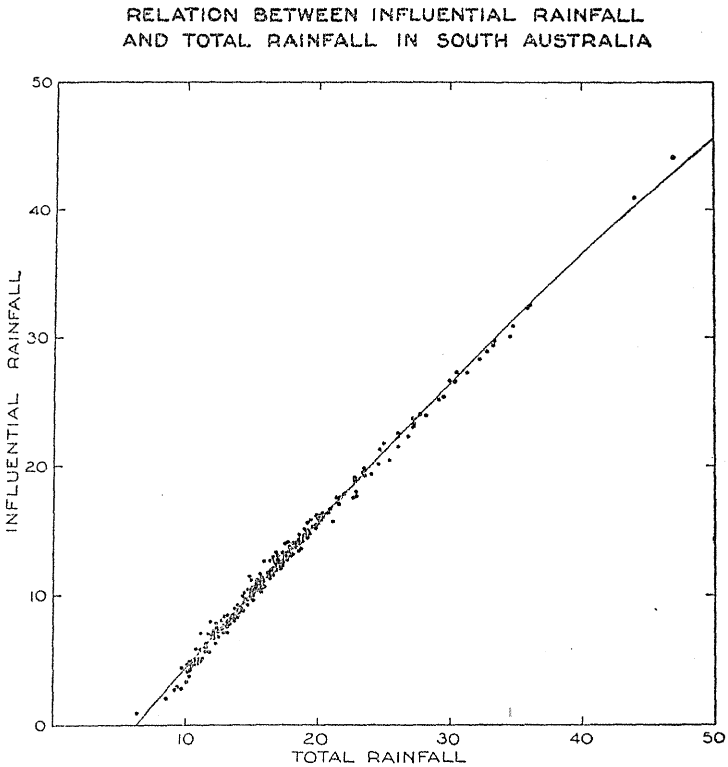

Fig. 5
Graph showing relation between mean annual rainfall and mean influential rainfall, South Australia.

A close relationship was found between the total rainfall and the influential rainfall. The curve (fig. 5) is close to a straight line but follows the relation $y = a + bx + cx^2$, where $a = -7{\cdot}6674$, $b = +1{\cdot}2431$ and $c = -0{\cdot}0035$. The value for c is significant. The graph indicates that rainfall in South Australia ceases to be effective in the neighbourhood of the 6″ annual isohyet.

Fig. 6 shows the mean yield of wheat per hundred, as given by Perkins (*loc. cit.*), plotted against the mean influential rainfall for each corresponding hundred. There is considerable variation in the quantity of wheat produced for each inch of influential rainfall, due to differences in natural soil fertility, the stage of settlement reached and the methods of farming practised. The maximum value is 1·76 bushels per inch; the minimum is 0·42 bushels per inch. Retentiveness of the subsoil is an important edaphic factor governing the efficiency of utilization of the rainfall available for the use of the wheat crop.

It is probable that an expression may be obtained which would relate and compare, for agricultural purposes, the climates of different countries. The starting point must be the delineation of the mean maximum growing season, as a period of time. This will be the period over which neither temperature nor lack of moisture inhibits the growth of agricultural plants. The march of the length of day and of the mean air temperature, and the form which these take over the growing period, will largely determine the types of plant which can be grown.

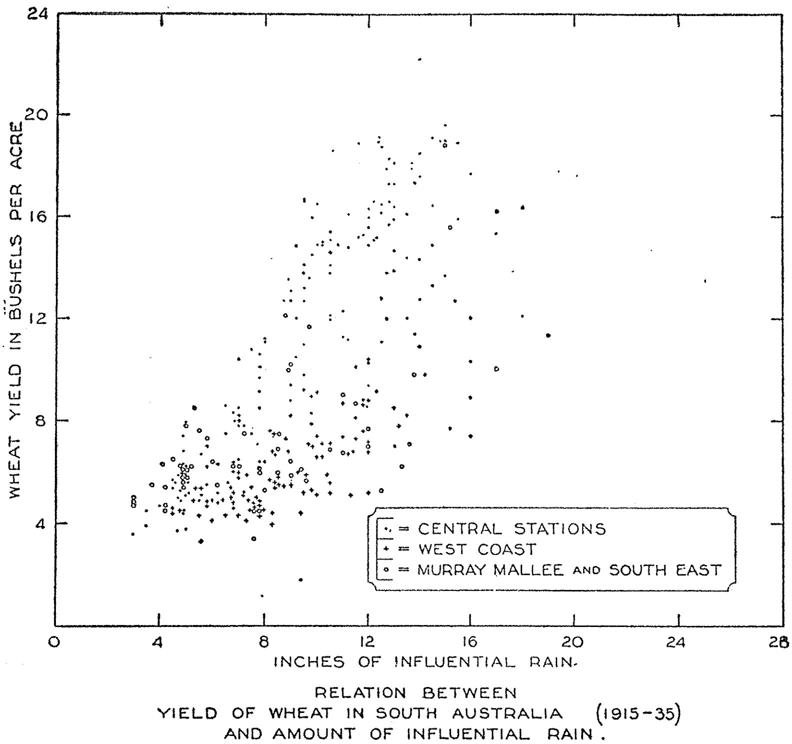

Fig. 6

Relation of the mean yield of wheat in South Australia (1915-35) and the amount of influential rain.

The arithmetic means employed in the present paper constitute a measure of average conditions only, but their relative stability enables them to be contrasted in a general way. The further step of determining the variability of the rainfall season and the amount of influential rainfall has not at this stage been attempted. The question of micro-climates is also a further problem which, naturally, should follow the separation of zonal types.

Zonation of Agricultural Areas in Terms of Vegetation, Soil and Climate

The climax vegetation, as a composite reflex of native soil and climatic conditions, affords a basis on which to construct and interpret the observed distributions of crop and pasture varieties.

The major types of association have been classified previously (26) from the pastoral viewpoint as follows:—(1) Sclerophyll forest, (2) Savannah woodland—(a) *Eucalyptus leucoxylon,* (b) *E. odorata,* (3) Dry savannah woodland (*E. odorata*), (4) Sclerophyll scrub and heath, (5) Mallee, (6) *Lomandra* with flats, (7) Shrub steppe, (8) Semi-desert scrub, (9) Desert. The agricultural districts are confined to the first six types of environment, the remainder being devoted to pastoral occupation. The region of change from wheat culture and mixed farming to purely pastoral production is indicated, approximately, by the 10″ annual isohyet, the lower limits of shrub steppe, the 5 months isochrone and the 5″ isohyet for influential rainfall. These lines do not necessarily coincide but rather congregate in the neighbourhood of what may be regarded as a marginal agricultural area.

The major types of climax vegetation, together with the geographical changes in the mean rain period and the mean influential rainfall, may be employed as delineators of climatic types, with which specific soil types are associated. Following the correlation of these measures of the native environment with the recorded distribution of livestock, wheat and seeded pasture, the portion suitable for permanent agricultural occupation has been classified on the basis of edapho-climatic zones, each fitted for a particular form of land utilization. These are shown in the accompanying Map III.

In this classification the edaphic and climatic types have for the most part been linked, but intrazonal soils occur. These include the heavy black soils, which resemble the rendzina type, the volcanic ash soils and the irrigated reclaimed swamps of the lower Murray River. The high natural fertility of these soils and their importance to South Australian agriculture warrant their individual separation at this stage.

The heavy black soils of the south-eastern portion have not previously been outlined *in toto*. Their location on this map has resulted from a study by the author of the original sectional surveys of the South Australian Lands Department, which are characterised by much practical detail, recording local changes in the type of vegetation and soil. This information was supplemented, where possible, by visual inspection.[4]

The zones have been grouped into four broad climatic classes, namely, temperate,[5] sub-temperate, semi-arid and arid, of which the arid group is outside the permanent agricultural area. This division is based on the length of the influential rain period, supported by vegetational changes. The four climatic classes differ considerably in the types of land utilization for which they are best fitted. The temperate group is characterised by conditions approaching those of southern Victoria, Tasmania, New Zealand and western Europe; the climate is suitable for the English and New Zealand types of pasture mixture, the production of root crops, potatoes, onions, etc., and the development of intensive agriculture, including dairying. The low fertility level of the soil over much of this area, however, limits the production of non-legumes and indicates a programme of land improvement based on suitable pasture legumes such as subterranean

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(4) Additional sources of information:—*(i)* Map of portion of the excessively wet South-Eastern lands, by W. J. Spafford (1922-25); *(ii)* "The Craters and Lakes of Mount Gambier, South Australia," by C Fenner, Trans. Roy. Soc. S. Aust., **vol. xlv**, pp. 169-205 (1921); *(iii)* "A Soil Survey of the Swamps of the Lower Murray River," by J. K. Taylor and H. G. Poole, C.S.I.R. (Aust.), Bull. 51 (1931).

(5) The term "temperate" is not used in the wide sense applied to the well-known world zones based on temperature, but in the restricted sense that temperate conditions of both humidity and temperature occur over all or nearly all the year.

clover, white clover and naturally occurring clovers and trefoils. The European grasses of low fertility requirement, such as *Holcus lanatus* and the *Agrostis* species, are adapted to these soils.

The sub-temperate group includes the podsolised soils, on which subterranean clover of the Mount Barker strain has provided the basis for agricultural development and soil improvement. Subterranean clover fails on the heavy black soils, although the climatic conditions associated with their occurrence are well suited to its development. The influential rain period within this group is materially shorter than in the temperate group, tending to inhibit the persistence of such herbage species as cocksfoot and white clover, and to restrict the production of summer-grown crops.

The division between sub-temperate and semi-arid conditions also separates the areas suitable for subterranean clover from those devoted to cereal cultivation and lucerne establishment. It also marks the region of edaphic change from podsolised sands to soils of the red-brown, grey mallee and wind-borne sandy types. Apart from the heath soils, the semi-arid area includes practically all of the land used for wheat culture in South Australia. Pasture development in this area depends on the use of deep-rooted perennials such as lucerne and evening primrose (*Oenothera odorata*) and on ephemeral legumes and grasses.

The outer limits of permanent cereal cultivation are indicated by the five months isochrone, and this has been used as a dividing line between the semi-arid agricultural area and the arid pastoral zone. Along the southern extremities of the arid zone is a marginal area, in its virgin condition, dominated chiefly by mallee, and in the eastern portion cleared for cereal cultivation, with resulting economic failure and widespread soil drift. Although a limited amount of cultivation may be possible in this area, climatic and edaphic considerations indicate that a perennial cover of vegetation is necessary to ensure erosion control and stability of occupation. No attempt has been made to separate edaphic types within the arid pastoral zone.

The following table summarizes the principal climatic, vegetational and edaphic features of the agricultural areas, together with the type of agriculture practised and the herbage plants considered to be most suitable for pasture development.

The zones described in the above table are for the most part clearly defined units characterised by specific vegetational, soil and climatic features. Zones 1, 2a and 2b are comparable in climate but differ widely in soil type; 2c is characterised by the presence of irrigation, and its type of agriculture is similar to that of 2a and 2b. Zones 3 and 4 exhibit a more critical summer period; their climatic features agree, but they differ widely in soil type. Zone 5 is a distinct edaphic type, comparable in rainfall to Zone 6. Zone 6 is characterised by the presence of red-brown and grey soils with retentive subsoils. The predominant form of vegetation is savannah, and this zone includes the most productive wheat areas of the State. Zone 7 is variable in edapho-climatic features but is characterised by mallee vegetation and the mallee soil type. The portion north of St. Vincent Gulf receives a short rainfall season, but this is compensated by the retentiveness of the subsoils. In terms of rainfall, the wheat yields of this portion are high. On Eyre Peninsula the rainfall season is longer, but this is offset by poorer subsoil retentiveness, with the presence of much limestone. Zone 8 is typical mallee, with a mean influential rain period of 5 to 6 months. Subsoil retentiveness in this zone is a major determinant of cereal production.

The above classification is necessarily on broad lines, but it provides for the zonation of agricultural land on basic considerations rather than empirically.

Table VII

Edapho-climatic zones of the agricultural areas of South Australia, together with the mean rainfall season, influential rainfall, natural vegetation, edaphic type, form of land utilization and herbage plants suitable for permanent pasture in each zone.

Zone	Mean Rainfall Season (Months)	Mean Influential Rainfall (Inches)	Natural Vegetation (Climax)	Edaphic Types	Forms of Land Utilization [6]	Herbage Plants Suitable for Permanent Pasture.
1	>9·0	>25	Sclerophyll forest	Podsolised sands	Livestock husbandry	*Trifolium subterraneum*, *T. repens*, *Holcus lanatus*, *Agrostis* spp.
2a	„	„	do	Volcanic ash soils	Intensive farming, including dairying	*T. repens*, *T. fragiferum*, *Lolium perenne*, *Dactylis glomerata*, *Phalaris tuberosa*, *Poa pratensis*.
2b	„	„	Open grassland	Friable black clays	do.	do.
2c	Irrigaton		—	do.	do.	do + *Paspalum dilatatum*, *H. lanatus*, *Bromus unioloides*.
3	7·5—9·0	15—35	Sclerophyll forest+savannah (*E. leucoxylon*)	Podsolised sands Lateritic soils	Livestock husbandry	*T. subterraneum*, Wimmera rye-grass *P. tuberosa*, *L. perenne*.
4	„	18—25	Open grassland	Friable black clays	do.	*T. fragiferum*, *Medicago lupulina*, *P. tuberosa*, Wimmera rye-grass.
5	6·0—7·5	10—18	Heath and scrub	Sands	do.	*Medicago sativa*, *T. subterraneum* (early flowering), *Oenothera odorata*, *P. tuberosa*, Wimmera rye-grass.
6	„	„	Savannah (*E. odorata*) + mallee	Red brown and grey soils	Cereal cultivation and livestock husbandry	*M. sativa*, *T. subterraneum* (early flowering), Wimmera rye-grass, *P. tuberosa*.
7	5·0—7·5	8—15	Mallee + dry savannah (*E. odorata*)	Mallee soils	Cereal cultivation with sheep and cattle.	*M. sativa*, *O. odorata*, *Wimmera* rye-grass, with early flowering ephemerals.
8	5·0—6·0	5—12	Mallee	do.	do.	do.

[6] Agricultural and pastoral only.

Summary

1. The principal climatic factors affecting the distribution of crop and herbage plants in South Australia have been examined and compared with the types of agriculture practised.

2. The nature and distribution of the agricultural flora appear to be governed principally by the seasonal relationship between length of day, temperature, rainfall and evaporation. The period of growth for agricultural plants is, however, essentially determined by the period of moisture availability, which varies considerably over the State.

3. The period of growth is conveniently approached by the concept of the "influential rain period", which is defined as the time interval over which the surface soil tends to be maintained above the wilting point for herbage plants. This is equivalent to the period over which rainfall exceeds, approximately, one-third of the evaporation (E) from the free water surface of a standard 36″ tank. Evidence is given for the use of the factor $0 \cdot \dot{3}E$. In the absence of sufficient stations with evaporimeter records, the relationship between saturation deficiency and evaporation may be used for the determination of the latter.

4. Over the agricultural areas, the mean annual period of influential rainfall varies from 5·0 months to more than 9·0 months. The 5·0 months isochrone corresponds with the outer limits of economic wheat culture, the 7·5 months isochrone with the limits of the standard strain of subterranean clover and 9·0 months isochrone marks the limits of white clover and European pasture mixtures.

5. The amount of rainfall available for the use of agricultural plants grown in the normal seasonal interval is termed "influential rainfall" and is defined as the quantity of rain falling within the influential rain period. This varies from 5·0 inches to more than 25·0 inches over the agricultural areas of South Australia. Soil type, in addition to climatic factors, markedly affects the yield of wheat in this State.

6. The major type of climax vegetation, together with the geographical changes in the mean rain period and influential rainfall, have been employed for the separation of edapho-climatic zones, each characterised by a particular form of agriculture. Maps showing the mean influential rain period in relation to wheat and pasture distribution, the amount of influential rainfall and the edapho-climatic zones of South Australia have been prepared.

Acknowledgments

The author desires to acknowledge advice from Mr. E. A. Cornish, B.Agr.Sc., on the statistical methods employed for curve fitting, and assistance from Mr. C. A. N. Smith, B.Agr.Sc., with the considerable amount of computational work involved. Thanks are also due to Messrs. E. J. Leaney and A. D. Cocks, who carried out the final delineation and photography, respectively, of the various maps and figures. Grateful thanks are due to officers of the South Australian Lands Department for the provision of facilities for the detailed examination of original sectional survey maps.

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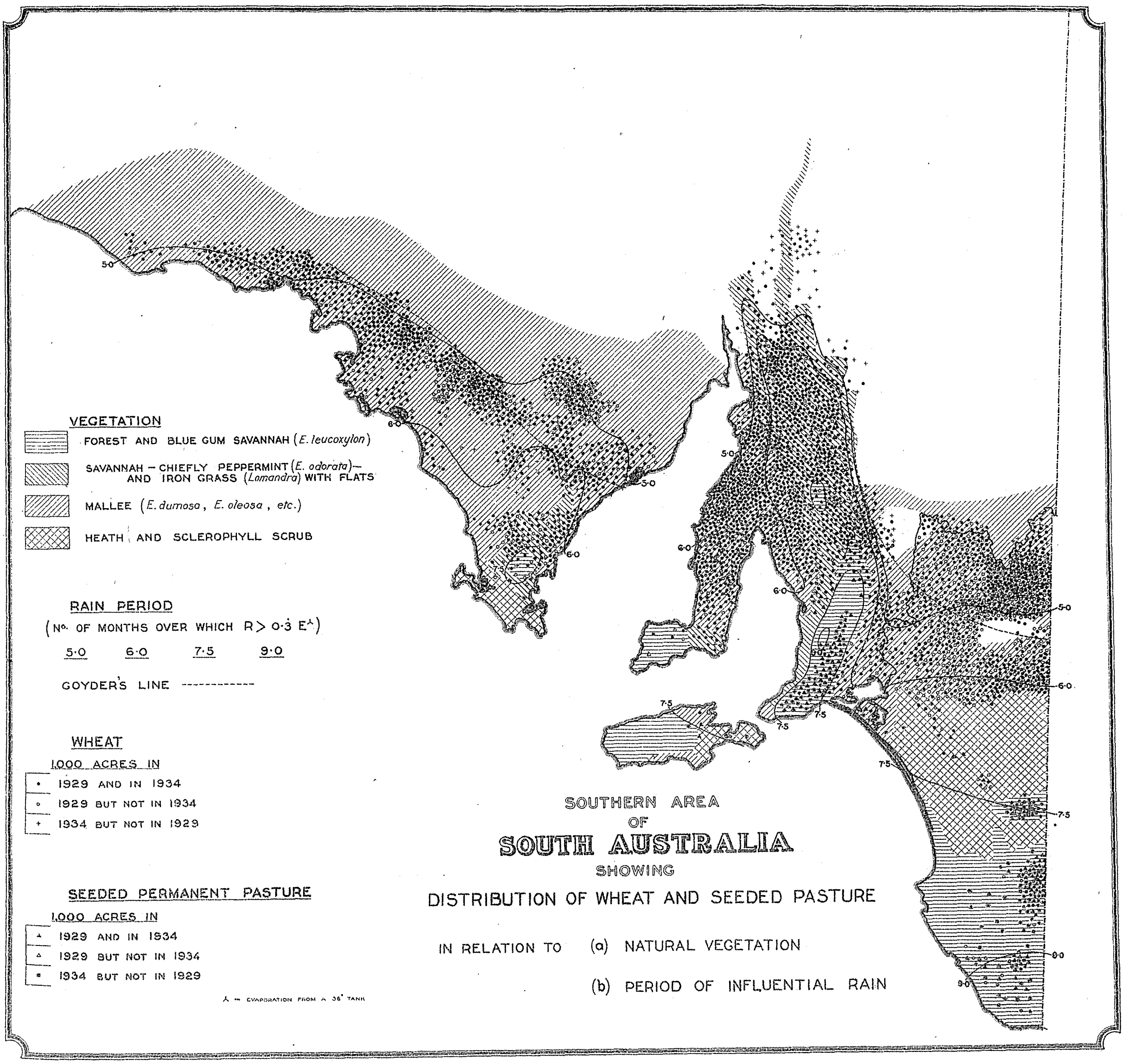

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