THE RELATIONSHIP BETWEEN EVAPOTRANSPIRATION AND GROWTH IN THE WHEAT CROP

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Summary

In trials conducted in 1961 and 1962 at Wagga in southern New South Wales, to investigate the yield physiology of wheat, the variety Heron was grown under various cultural treatments. This paper deals with the relationship of evapotranspiration to crop growth.

Vegetative growth at a given date in the spring was influenced markedly by time of sowing and fertilizer application, and to a lesser extent by sowing rate. Large differences in vegetative growth caused relatively small differences in evapotranspiration rate when soil moisture was adequate. An increase in total dry weight of 100 g/m^2 in early October was associated with an increase in cumulative evapotranspiration up to that time of about 0·50 in.

It was concluded that although a reduced fertilizer application and reduced sowing rate (below 30 lb seed per acre) permitted higher soil moisture levels at flowering, this necessarily involved a considerable reduction in total dry weight at flowering. With delayed time of sowing, the post-flowering moisture status of the crop can be expected to deteriorate, primarily because of delayed flowering date.

I. INTRODUCTION

A common observation in cereal crops grown with limited moisture is that high levels of vegetative growth may depress grain yields. This is particularly important in southern New South Wales, where soil fertility is often high because of the inclusion of leguminous pastures in the cropping rotation. High soil nitrogen stimulates vegetative growth but grain yield responses are sometimes small or even negative, a phenomenon which is termed locally "haying off" (Colwell 1963).

Other workers have reported similar results in dry-land fertilizer trials with cereals (Ramig and Rhoades 1963; Barley and Naidu 1964). It has generally been suggested that rapid vegetative growth leads to increased moisture usage (evapotranspiration) early in the season, and that less soil moisture therefore is available to sustain grain growth after flowering. Early theory suggested that water use was independent of crop growth once the crop had completely covered the ground (Penman 1956). More recently, however, it has been suggested that this is often an oversimplification (Penman 1961; Viets 1962), and it is not altogether clear to what extent the parameters are related. The only work with cereals in Australia has been that of Barley and Naidu (1964), who reported recently that added nitrogen, sufficient to stimulate the production of dry matter, did reduce the level of soil moisture at ear emergence of wheat.

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The aim of the trials reported here was to determine the extent to which stimulation of vegetative growth of the wheat crop increases evapotranspiration and, in turn, plant moisture stress, and to study the subsequent effects on grain yield. Differences in vegetative growth were achieved through variations in the time of sowing, rate of sowing, and amount of fertilizer applied. This paper reports the subsequent effects on the evapotranspiration of the crop. Other results are reported in later papers.

TABLE 1

CLIMATIC DATA FOR WAGGA WAGGA

Month	Rainfall* (in.)			Mean Evaporation † (in./day)			Av. Daily Mean Temp. (°F)		
	1961	1962	Long-term Average	1961	1962	Long-term Average	1961	1962	Long-term Average
January	0·87	4·22	1·34			0·287			75·6
February	0·08	0·80	1·69			0·243			75·8
March	0·91	1·76	1·59			0·194			70·5
April	2·22	0·68	1·57			0·125			61·2
May	0·19	2·41	1·71	0·076	0·063	0·065	48·4	52·9	53·8
June	1·80	0·79	2·12	0·044	0·050	0·042	46·8	50·6	48·4
July	2·58	1·54	1·82	0·036	0·053	0·039	43·8	46·1	47·5
August	2·99	2·31	1·88	0·066	0·064	0·057	47·1	47·6	50·0
September	1·07	1·35	1·69	0·103	0·098	0·090	50·9	50·9	54·9
October	1·15	1·73	2·05	0·208	0·106	0·133	60·3	54·1	60·9
November	4·15	0·82	1·57	0·221	0·230	0·193	65·2	64·4	67·4
December	3·10	1·95	1·64			0·261			73·1
Year	21·11	20·36	20·67						61·9

* Long-term average, Wagga Agricultural College, 1913–1962.

† Australian Standard Evaporation Tank, average, 1948–1963 (Soil Conservation Station, Wagga).

II. Experimental Details

Trials were conducted at the Agricultural Research Institute, Wagga Wagga, N.S.W., in 1961 and 1962. Important features of the climate are summarized in Table 1. There is a winter growing season of about 7 months, with an April to October rainfall of 12·8 in. Conditions in 1961 and 1962 were close to average, but it is important to note that rainfall was low and evaporation was high in September and October of 1961. Details of trials and treatments are shown in Table 2.

All trials were on Gombalin clay loam, a typical red-brown earth, in which the brown clay loam topsoil passes at about 9–12 in. into a heavy red-brown clay which becomes yellower and heavier below about 30 in. Except for trial SN62, the land had been under subterranean clover pastures for several years. It was ploughed in the spring, and cultivated according to the usual practice in preparing for sowing in the subsequent autumn and winter. Under such conditions the levels of available soil nitrogen were high: nitrate nitrogen at soil depth 0–12 in. in mid August exceeded 20 p.p.m. Land used for the SN62 trial had never grown subterranean clover, and had been cropped the previous year; thus it had a low level of nitrogen fertility, the nitrate nitrogen level of unfertilized soil at depth 0–12 in. being about 4 p.p.m. in mid August.

TABLE 2

SUMMARY OF TRIALS AND TREATMENTS

Trial	Treatment				
	Symbol	Date Sown	Rate of Sowing (lb/acre)	Superphosphate (lb/acre)	Nitrogen (lb/acre)
Time of sowing, 1961 (T61)	T_1	April 28	60	224	Nil
	T_2	May 22	60	224	Nil
	T_3	June 8	60	224	Nil
	T_4	June 29	60	224	Nil
	T_5	July 18	60	224	Nil
Time of sowing, 1962 (T62)	T_1	May 4	60	224	Nil
	T_2	May 21	60	224	Nil
	T_3	June 7	60	224	Nil
	T_5	July 16	60	224	Nil
Rate of sowing, 1961 (R61)	R_1	June 9	30	224	Nil
	R_2	June 9	60	224	Nil
	R_3	June 9	120	224	Nil
Rate of sowing, 1962 (R62)	R_1	June 8	20	224	Nil
	R_2	June 8	60	224	Nil
	R_3	June 8	120	224	Nil
	R_4*	June 8	20	224	Nil
	R_5†	June 8	20	224	Nil
Fertilizer, 1962 (SN62)	S_0N_0	June 9	85	Nil	Nil
	S_0N_1	June 9	85	Nil	100
	$S_{\frac{1}{2}}N_0$	June 9	85	56	Nil
	$S_{\frac{1}{2}}N_1$	June 9	85	56	100
	S_2N_0	June 9	85	224	Nil
	S_2N_1	June 9	85	224	100

* Wide rows (21 in.)

† Wide rows (21 in.) plus inter-row straw.

The variety Heron, which was used in all trials, was drilled in 7-in. rows. Superphosphate (22% P_2O_5) was drilled with the seed, while nitrogen, as sulphate of ammonia, was top-dressed onto the plots on July 20 (three-leaf stage). The straw mulch of treatment R_5 in trial R62 was spread between the rows at the rate of about 2·5 tons per acre after seedling emergence. Fallow spraying with 2,4-D, early hand-hoeing, and vigorous crop growth kept weed growth at negligible levels on the high fertility land. In trial SN62 on the low fertility land, however, no attempt was made to control the marked growth of ryegrass (*Lolium rigidum*) in some treatments; growth of this weed was measured along with that of the wheat crop.

Treatments were arranged in randomized blocks, but in trial SN62 superphosphate main plots were split for nitrogen application. Depending on the site and number of treatments, three to six replicates were sown. All plots were 30–36 ft long; they were nine rows wide (5·3 ft) in the time and rate of sowing trials in 1961 (trials T61 and R61) and 16 rows wide (8·3 ft) in all other trials. The plots were divided into a number of sampling locations, and crop samples were taken during the season by quadrat cuts at these locations.

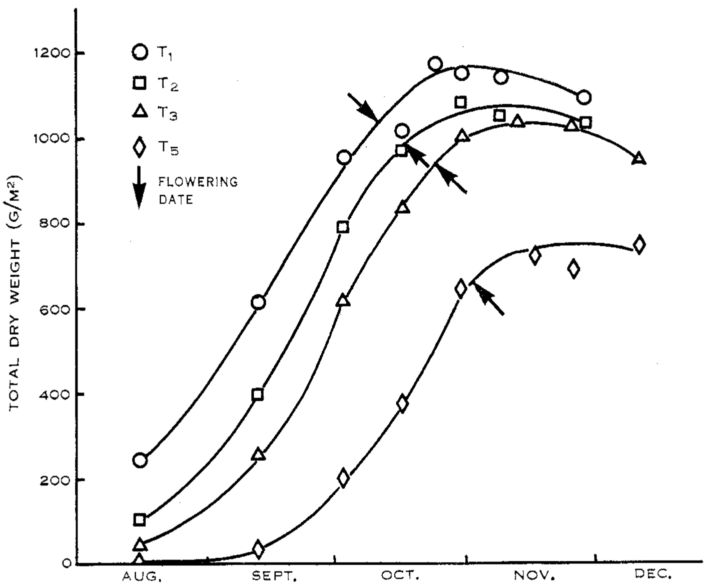

Fig. 1.—Total dry weight (W) changes with time: trial T62.

In 1961, soil moisture contents were determined gravimetrically with auger sampling to 48 in. at 6-in. intervals. Sampling coincided with crop growth harvests; the two auger holes per plot were located in the centre of quadrats at which a cut had just been made. In 1962 a neutron moisture meter (model TR, Soilab, Adelaide) was used to follow soil moisture changes. This instrument was similar to that described by Holmes and Jenkinson (1959). Two black Polythene access tubes were installed to a depth of 53 in. in each plot during the winter (62 in. for treatment T_1, trial T62). Counts were taken at 9-in. intervals, beginning with the source at 12 in. below the surface. The top 7·5 in. of the profile was sampled by auger, and moisture contents determined gravimetrically. The moisture meter was calibrated by using both moist soil samples, taken when the access tubes were installed in the winter, and drier samples taken near the access tubes after the final crop harvest. Bulk density measurements of the soil were also made. Since the regression of counting rate on moisture content was significantly different between some of the depth intervals sampled, a separate calibration was used for each interval.

III. Results

(a) Cumulative Evapotranspiration and Crop Growth

Cumulative evapotranspiration (ΣE_a), i.e. the total amount of evapotranspiration from the earliest time of sowing for each particular trial, was calculated from changes in soil moisture and rainfall data. There was no evidence that crop roots or drainage removed significant amounts of water below 48 in.

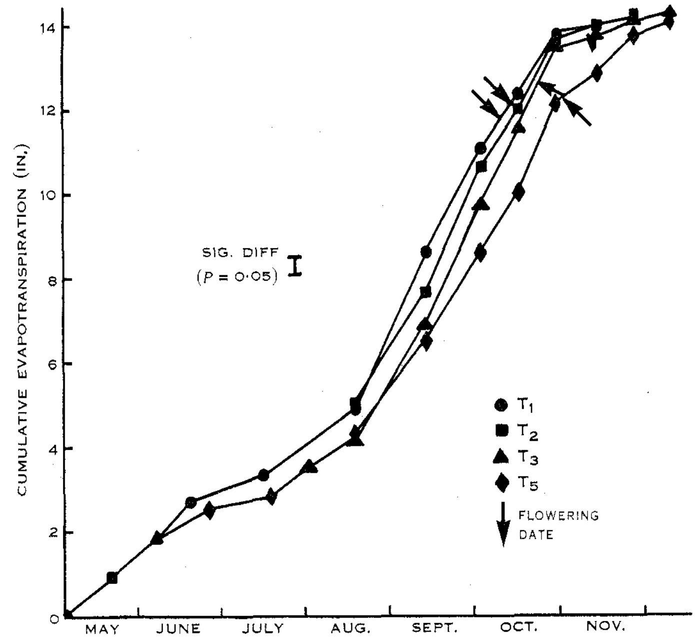

Fig. 2.—Cumulative evapotranspiration (ΣE_a) changes with time: trial T62.

In each trial, treatments which had large effects on crop growth (total dry weight of tops, *W*) also significantly affected ΣE_a. Figures 1 and 2 show the changes with time in *W* and in ΣE_a, respectively, for trial T62.

In this trial, differences in ΣE_a associated with differences in total growth increased in the early spring, reaching a maximum in late September, and then diminished to an insignificant level at crop maturity in December. In all other trials, the ΣE_a differences were also greatest about September–October. These differences were not, however, completely eliminated at the time of crop maturity in the fertilizer trial in 1962. Table 3 shows the largest treatment differences in ΣE_a and the corresponding differences in total crop growth for each trial.

The largest differences in ΣE_a recorded for the trials were about 2 to 2·5 in., and were associated with extreme differences in crop growth caused by a wide range in sowing times or in levels of soil fertility. Sowing rate, within the range studied and under the high soil fertility conditions, had a smaller effect on crop growth and on ΣE_a in the spring; however, under wide-row spacing, as compared with the

TABLE 3

CUMULATIVE EVAPOTRANSPIRATION (ΣE_a) AND TOTAL DRY WEIGHT (W) AT THE TIME WHEN TREATMENT DIFFERENCES IN ΣE_a WERE GREATEST FOR EACH TRIAL

Trial	Treatment	Date	ΣE_a (in.)	W (g/m²)
T61	T_1	Sept. 26	9·98	929
	T_2		8·93	693
	T_3		8·84	546
	T_4		8·19	290
	T_5		8·00	185
	L.S.D. ($P = 0·05$)		0·47	
T62	T_1	Oct. 10	11·67	984
	T_2		11·28	881
	T_3		10·63	725
	T_5		9·30	290
	L.S.D. ($P = 0·05$)		0·40	
R61	R_1	Oct. 12	10·25	640
	R_2		10·65	675
	R_3		10·83	772
	L.S.D. ($P = 0·05$)		0·55	
R62	R_1	Oct. 4	6·88	427
	R_2		6·97	667
	R_3		7·76	701
	R_4		6·18	377
	R_5		6·07	366
	L.S.D. ($P = 0·05$)		0·78	
SN62*	S_0N_0	Oct. 17	7·80	289
	S_0N_1		8·30	436
	$S_{\frac{1}{2}}N_0$		7·90	389
	$S_{\frac{1}{2}}N_1$		9·63	680
	S_2N_0		8·31	448
	S_2N_1		9·70	800
	L.S.D. ($P = 0·05$)		0·80	

* W for trial SN62 includes weed material, which was less than 20% of W for all treatments except S_0N_1, where it was approximately 50%.

conventional narrow rows at the same sowing rate, ΣE_a was significantly smaller. Straw mulch between these wide rows failed to conserve a significant amount of moisture.

(b) *Evapotranspiration Rate*

Evapotranspiration rates varied from 0·05 in. per day during the winter to 0·16 in. per day in the spring for dense crops when soil moisture was high. As maturity was approached, rates approached zero. Changes in evapotranspiration rates are related in part to seasonal changes in radiation. Such changes can be allowed for to some extent by calculating the ratio of evapotranspiration rate to pan evaporation rate (Australian Standard Tank), which was measured 1 mile from the trial sites. Figure 3 shows typical time changes in this ratio (E_a/E_p) for the time of sowing trial in 1962.

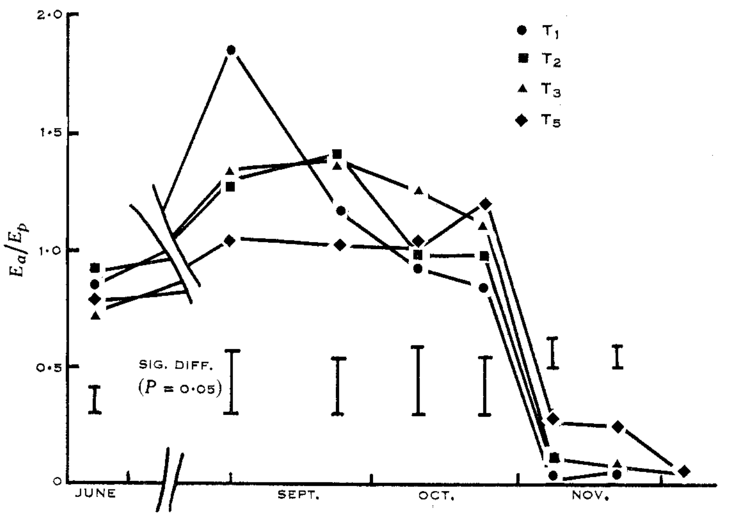

Fig. 3.—Changes in the ratio of evapotranspiration to pan evaporation (E_a/E_p) with time: trial T62.

During the winter, when the total amount of crop growth was small, E_a/E_p ratios were within the range 0·70 to 0·90 for all trials. Maximum E_a/E_p ratios in the spring were from 1·30 to 1·50 for dense crops with one exception, treatment T_1 during late August and early September in trial T62 (Fig. 3). In this instance the ratio was 1·86, significantly higher than that for other treatments. Figure 3 also shows the marked fall in the ratio E_a/E_p which invariably occurred in the late spring.

The association between evapotranspiration and crop growth can be examined more closely in the relationship of the ratio E_a/E_p to the mean leaf area index (L) during various periods when soil moisture was adequate (Fig. 5). Leaf area index refers to the area of all green tissue (leaves, stems, and head) in the crop per unit area of land (details of its determination are given in a later paper). Figure 4 shows time changes in L for trial T62. In Figure 5 it is seen that for each unit increase in L, the ratio E_a/E_p, and therefore the evapotranspiration rate, increased by about 10–15% of its value when L was close to zero. Linear regressions are shown, although it is realized that E_a/E_p cannot increase indefinitely, and that therefore a curvilinear relation may be involved at higher L values.

Since E_a/E_p declined earlier in late spring with the denser crops, low soil moisture most probably restricted evapotranspiration. It is difficult in this type of experiment to obtain precise information on this point, since other factors also tend to decrease E_a/E_p in the late spring. These factors include increasing potential evapotranspiration rates (Denmead and Shaw 1962), decreasing leaf areas, and decreasing topsoil moisture, which would reduce the component of evapotranspiration arising from direct soil evaporation. Data from the SN62 trial, however, show the effect of a

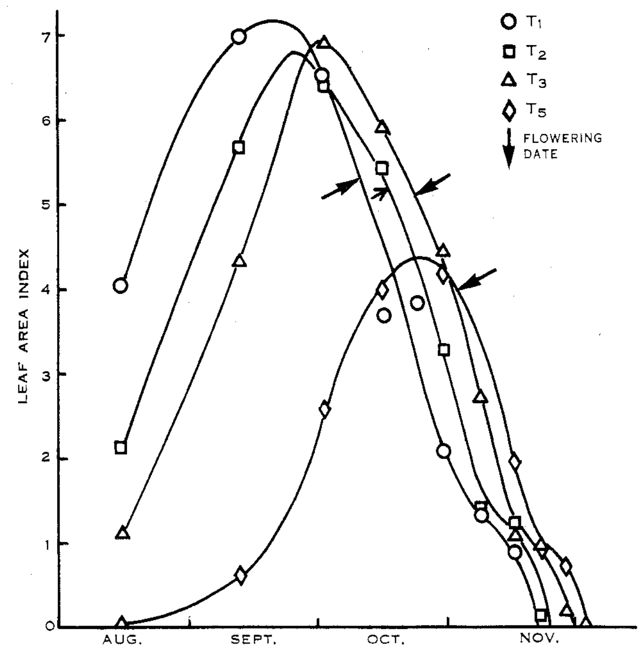

Fig. 4.—Leaf area index (L) changes with time: trial T62.

decrease in available soil water on evapotranspiration rate (Fig. 6). Available soil water refers to the amount, in milligrams per cubic centimetre and averaged over the whole rooting zone, by which the soil moisture content is greater than the —15 bar value; when the soil was dried to less than this water content its value became negative.

In trial SN62 (Fig. 6) it is seen that even before L began to decrease in the later spring, the ratio E_a/E_p for the two dense crops (treatments $S_{\frac{1}{2}}N_1$ and S_2N_1, $L = 3\cdot8$ and $5\cdot0$ respectively) had decreased by about 40% as available soil water fell from about 40 mg/c.c. to about 10 mg/c.c., corresponding approximately to a decrease in mean soil water potential from —3 bars to —10 bars. This occurred during a period when there was no change in pan evaporation to confuse the picture, and when E_a at the beginning of the period was 0·15 in. per day. Other treatments in this trial showed more gradual decreases in E_a/E_p as soil moisture stress rose; however, these changes are confounded by concomitant decreases in L.

IV. Discussion

Under conditions of adequate soil water, evapotranspiration rates increased as leaf area index and crop growth increased, regardless of the treatment causing the increase in crop growth. Evapotranspiration was related linearly to crop growth. However, changes in evapotranspiration rate were small relative to changes in

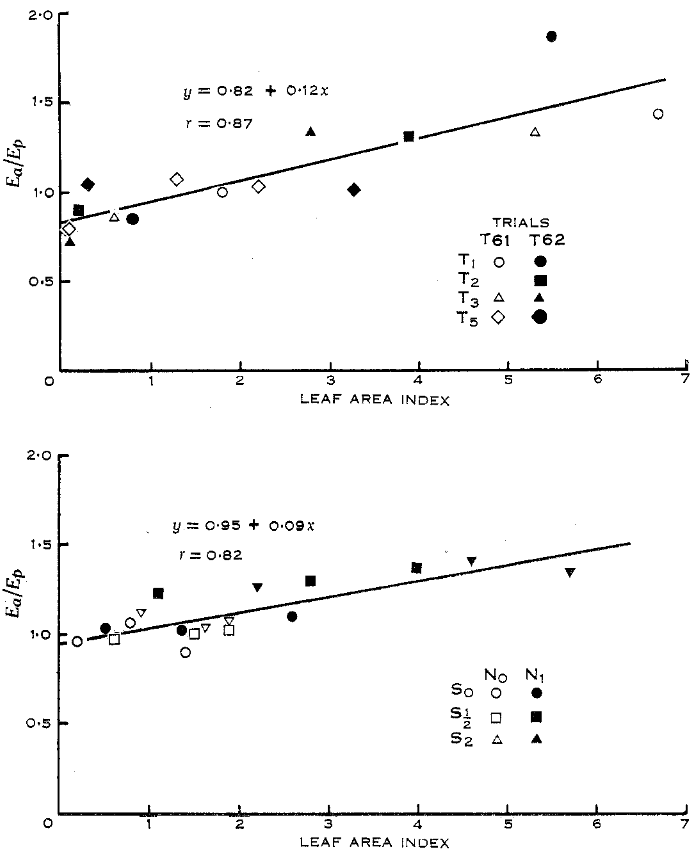

Fig. 5.—Relationship between the ratio of evapotranspiration to pan evaporation (E_a/E_p) and leaf area index (L) for periods when the crop was adequately supplied with water: trials T61 and T62, and SN62.

growth, and evapotranspiration was considerable even when the amount of growth was very small (Table 3). Such a relationship is commonly found for crops grown under conditions of adequate soil water (Viets 1962).

Increased crop growth tends to increase the transpiration component of evapotranspiration for two reasons: (1) the greater leaf area of the crop increases its interception of solar radiation; (2) a greater leaf area, crop height, and crop roughness reduce the proportion of this intercepted radiation which is lost as sensible heat to the air and, under conditions of horizontal advection, increases the amount of sensible heat gained from the air by the crop (Lemon, Glaser, and Satterwhite 1957; Penman 1961). The dependence of evapotranspiration on crop growth, however, is weakened by evaporation from the soil surface when it receives radiation and is wet; or, when crop leaf area becomes large enough, by the complete interception of solar radiation by the crop, since further increases in leaf area do not further increase the radiation intercepted.

The relationship of evapotranspiration to growth reported here is the product of these two opposing sets of factors as outlined above. During the winter and early spring (August), the topsoil remained continually moist owing to frequent rains and

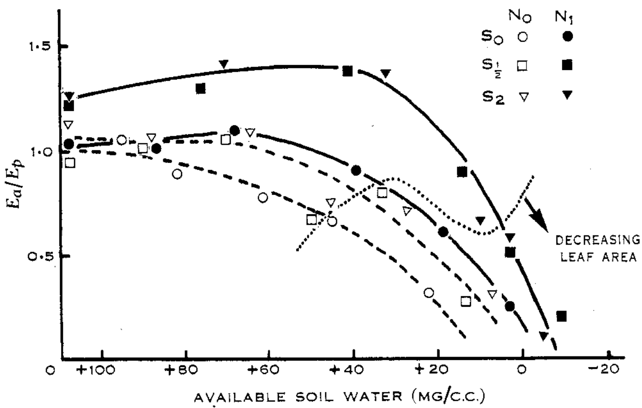

Fig. 6.—Relationship between the ratio of evapotranspiration to pan evaporation (E_a/E_p) and available soil water (see text). Unbroken lines represent N_1 treatments and dashed lines N_0 treatments. $S_{\frac{1}{2}}$ and S_2 are considered together, being represented by the same lines. Beneath the dotted line, leaf areas were less than the maximum values for each treatment. Trial SN62.

low evapotranspiration rates; thus the response of evapotranspiration to several-fold increases in crop growth was small (Figs. 1, 2, 3). The values of E_a/E_p during the winter agree with those of McIlroy and Angus (1964) for evaporation from wet soil relative to Australian Standard Tank evaporation. Larger absolute differences in crop leaf area and height, increasing radiation and possibly also horizontal advection, and drier topsoils probably accounted for the dependence of evapotranspiration on crop growth during September and October. Reduced soil moisture, along with the decline in leaf area, prevented a continuation of this differential in evapotranspiration rates, and placed an upper limit on the divergence of cumulative evapotranspiration as between dense and sparse wheat crops.

The data of Figure 6 indicate a 40% fall in the E_a of the wheat crop relative to potential evaporation at a mean soil water potential of about −10 bars. Denmead and Shaw (1962), working with corn grown in sunken 20-gal containers, showed that a similar drop in E_a at similar potential evapotranspiration levels (i.e. 0·15 in. per day) occurred at only −2 to −4 bars soil water potential. Perhaps a greater water conductivity existed in the soil–root system of the wheat because of a larger volume of soil for root exploration, or perhaps the wheat roots were still extending into moister deep layers of the profile at the time.

As Viets (1962) pointed out, interactions of crop type with advected energy may alter the response of evapotranspiration to treatment in small plots relative to the response in normal-sized fields. One complicating effect is the exaggeration of the oasis effect in small plots. The oasis effect operates when energy moves horizontally to a crop from drier surroundings (Halstead and Covey 1957; Millar 1964). Thus conditions surrounding a trial for some distance will tend to override and obscure treatment effects on evapotranspiration. McIlroy and Angus (1964) reported a mean E_a/E_p of 1·05 for short grass at Aspendale; they considered this value indicative of oasis effects. Thus the higher ratios (1·3 to 1·5) generally recorded in the Wagga trials in the spring may indicate that evapotranspiration rates were also increased by oasis effects. It is difficult, however, to estimate whether treatment effects would have been altered relative to their effects in fields of normal size. The values of E_a/E_p are probably not artificially high, since trial sites were buffered by 1–10 chains of surrounding crop; also the values are similar to those of Butler and Prescott (1955) and Slatyer (1956), when calculated on the basis they used ($E_a/E_p^{0·75}$, expressed in inches per month). For reasonably dense crops adequately supplied with water in our trials, values of $E_a/E_p^{0·75}$ ranged from 1·32 to 1·90 (with one value 2·28), with a mean of 1·65. These values are within the range reported by Butler and Prescott for wheat in South Australia (1·8 to 2·1 for crops with adequate water) and are not greater than the maximum $E_a/E_p^{0·75}$ (2·4) to be expected under optimum conditions according to these authors. Slatyer (1956) found maximum values of about 1·8 for several crops.

A second complication in interpreting evapotranspiration data from small plots arises from the "clothes-line effect". This refers to increased or decreased wind movement through a plot because of its relatively exposed or sheltered position. The effect is particularly important if treatments induce height or crop-density differences (Tanner 1960). Height differences up to 20 in. between extreme treatments did arise in these trials, and the possibility that differences in evapotranspiration may be overestimated cannot be excluded. Until more is known about the magnitude of these small plot errors, use of larger plot sizes in evapotranspiration studies seems desirable.

Despite the qualification that the effect of treatment differences on evapotranspiration rate may have been overestimated, practical conclusions can be drawn. Total moisture available to the crops in 1961 and 1962 was about average, and the pattern of evapotranspiration, with the onset of moderate to severe moisture shortage some time in October, can be taken as reasonably typical for the wheat crop at Wagga.

(a) *Fertilizer and Sowing Rate*

Restriction of vegetative growth by low phosphorus and nitrogen nutrition or by a reduced sowing rate where soil fertility was high, did conserve some moisture for the post-flowering period (flowering was in mid October). Whether the small gain in soil moisture relative to the large reduction in vegetative growth (about 0·50 in. gain for each 100 g/m² reduction in W at flowering) would lead to an increased grain yield depends on the degree to which soil moisture at flowering substitutes for W in determining subsequent grain production. It was also evident that reduced sowing rate did not markedly restrict vegetative growth, let alone evapotranspiration, unless the rate of sowing was reduced below 30 lb of seed per acre.

(*b*) *Time of Sowing*

The date of flowering was delayed in a consistent manner by later sowing (Table 4). At a given time in the spring, cumulative evapotranspiration (ΣE_a) was greater for earlier-sown crops, but because of the delayed development, ΣE_a at a given stage of development, e.g. flowering, was somewhat greater for later-sown crops (Table 4). It is expected that this pattern would be fairly consistent, provided there is reasonably adequate soil water until flowering, since it depends on the seasonal trend in potential evapotranspiration rates.

TABLE 4

PREDICTION OF DIFFERENCES IN TOTAL SOIL MOISTURE AT FLOWERING AS AFFECTED BY TIME OF SOWING

Detail	Year	Treatment		
		T_1	T_3	T_5
Date of sowing	Mean	May 1	June 8	July 18
Date of flowering	Mean	Oct. 8	Oct. 19	Oct. 28
Cumulative evapotranspiration from sowing of T_1 (ΣE_a) to flowering (in.)	1961	10·95	11·40	12·05
	1962	11·80	12·45	12·20
Difference in ΣE_a to flowering compared with T_1 (in.)	Mean	—	+0·55	+0·75
Predicted average difference in total soil moisture at flowering compared with T_1 (in.)	—	—	+0·15	+0·45
Actual difference in total soil moisture at flowering compared with T_1 (in.)	1961	—	+0·43	+0·01
	1962	—	+0·59	+1·06

To relate these differences in ΣE_a at flowering to the expected differences in total soil moisture at flowering (Table 4), it is necessary to know the rainfall for the period between flowering of the various crops. The average rainfall expectancy is about equal for September, October, and November, being approximately 0·06 in. per day. The mean delay in flowering of treatment T_3 relative to T_1 was 11 days, and of T_5 relative to T_1 was 20 days, periods during which one would expect on the average about 0·70 and 1·20 in. of rain respectively.

If these rainfall totals are added to the corresponding mean differences in ΣE_a from Table 4, and if ΣE_a and development patterns are consistent, one would expect, on the average, a slight gain in total soil moisture with delayed sowing (row 6 of Table 4). This was the case in 1962 and partially so in 1961, despite the rainfall variations of a particular season.

Although later-sown crops may be slightly favoured as regards the amount of water available at flowering, this must be considered in relation to the expected rates of usage in the post-flowering period. Evapotranspiration at a given time in October is not very different for various times of sowing (Fig. 3), and can be estimated satisfactorily for these purposes by pan evaporation. The mean expected difference between pan evaporation and rainfall for a period of 3 weeks after the flowering dates of treatments T_1, T_3, and T_5 (i.e. October 8, 19, and 28 respectively) increases considerably, being 0·08, 0·11, and 0·13 in. per day respectively. Thus it can be anticipated that a given quantity of water at flowering would maintain a given rate of E_a relative to E_p for only 60% as long after flowering for T_5 as for T_1. The onset of plant moisture stress (turgor loss) is related to a fall in the ratio of actual evapotranspiration to potential evapotranspiration (Denmead and Shaw 1962). From this observation and the above calculations it is apparent that on the average, plant moisture stress after flowering would increase in severity with later sowings. This conclusion is actually reinforced by the direction of small plot errors to be expected in these trials. These data thus indicate experimental confirmation of the improvement in the water relations of the wheat crop after flowering, associated with earlier sowing and with earlier flowering in the spring.

V. Acknowledgments

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