Relationship between Time of Anthesis and Grain Yield of Wheat Genotypes with Differing Developmental Patterns

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Abstract

This paper reports studies of the effects of time of planting and genotype on wheat grown with and without irrigation in Queensland.

Under irrigation, and in the absence of frost damage, the grain yield of a number of semidwarf wheat genotypes was highest when anthesis occurred in midwinter. There was a linear decline in grain yield with departure from this anthesis period, associated with rising evaporative demand and daily mean temperature. Genotype variation in this yield pattern was due to different growth durations and in particular to the leaf areas developed by anthesis, which were often limiting yield especially in very early planting of quick genotypes. Under dryland conditions similar patterns of grain yield variation with anthesis date occurred, although the genotype variation about this pattern depended upon the interaction between growth duration and leaf area development on the one hand, and water use on the other.

These results suggest that some consideration be given to altering the agronomy, in regions of low frost risk, to take advantage of the higher yield potential associated with midwinter anthesis dates.

The effects of growth duration, anthesis date and environment could be integrated into a yield index of the form

$$\text{Grain yield index} = a + b(T/E_0) \times (1/T_m),$$

where a and b are constants, T, E_0 and T_m are transpiration (mm), pan evaporation (mm) and mean daily temperature (°C) respectively, all estimated or measured within $\pm$ 10 days of anthesis ($r^2 = 0 \cdot 801$, $n = 112$).

The regression slope was constant across sites, times of planting and irrigation treatments for closely related semidwarf genotypes, but was significantly lower for a group of taller wheats tested. These groupings were associated with differences in grain number per m^2.

The similarity between this yield index and the crop growth index of de Wit suggests that grain yield in wheat is closely linked to the growth potential over a short period around anthesis.

Introduction

In the Queensland wheat belt, the chance of receiving a significant rainfall during a given week is extremely low in the autumn–winter period, but rises rapidly as summer approaches. Because of the low and erratic autumn–winter rainfall there are large variations in planting date and a need, at times, to plant relatively long-season wheats if flowering is to take place after the period of frost risk. This variation in planting date, together with the low rainfall during the growing season, leads to the mean wheat yield in Queensland varying by a factor of four from year to year. The quantity of stored soil water present at planting is a very important determinant of grain yield (Waring *et al.* 1958; Woodruff 1975).

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Previous attempts to explain this yield variation by means of simple soil water budgets have used relatively inflexible inputs of plant growth and hence water demand. Nix and Fitzpatrick (1969) and Berndt and White (1976) explained 69 and 76% respectively of the wheat yield variation by using an index of available soil water at heading and the expected 'A' class pan evaporation in the next 3 weeks. The use of wheat cultivars of greatly differing phenologies, however, introduces changes in pre-anthesis growth and, as a result, the water demand in this period. This paper presents the results of several trials comparing the growth and yield of genotypes with a range of development patterns. The wheat crops were planted over a wide range of dates and at many dryland and irrigated sites in the Queensland wheat belt. An attempt is made to determine from these results the influence of factors, especially those operating around anthesis, on the relative yields of these cultivars, and to allow for varying vegetative development by introducing the concept of water use or transpiration over the period around anthesis instead of water stress.

Methods

Wheat genotype × planting-time studies, some involving full irrigation, were conducted in various regions of the Queensland wheat belt between 1974 and 1979. The cultivar WW15, which is a parent of many of our current wheat varieties, was incorporated as a standard in all trials and seeding rates were adjusted to give the same seed number as 45 kg ha^{-1} (dryland) and 70 kg ha^{-1} (irrigated) of WW15. Plant dry weight, tiller number, and leaf area were measured on two 3-row quadrats (1 m long) taken from each plot at anthesis. At anthesis, soil water status throughout the soil profile, or to a depth of 120 cm if deeper, was determined gravimetrically by two soil cores taken in each plot. The leaf area index (LAI) and soil water status measured at anthesis (A) were combined to provide an estimated transpiration (T) over the period A±10 days from whichever of the following equations gave the lower value:

$$T(\text{mm}) = 16W^2, \tag{1}$$

(with a minimum of 0·8 mm day^{-1} (if available) (1a)

$$T = E_0\,[1 - \exp(-0{\cdot}5\text{LAI})], \tag{2}$$

where W is fractional available water in the rooting zone and E_0 is mean daily 'A' class pan evaporation.

Anthesis date was taken as that date when 50% of main stems showed anthers. Equation 1 was developed by Linacre (1973) and confirmed by Johns and Smith (1975) and the restriction (1a) is from D. R. Woodruff (unpublished observations), and equation (2) is from Al-Khafaf *et al.* (1978) and has been found to fit water-use data in Queensland (D. R. Woodruff, unpublished observations).

Final grain yield was measured from 6-m^2 hand-cut quadrats, except at Emerald and Miles, where nine-row plots (20 m long) were machine harvested. All grain yields and 1000-kernel weight results are presented at 13·5% moisture. Of the genotypes used in these trials cvv. Banks, Cook, QT4144 and Timgalen were then resistant to stem rust. Control measures taken to control infection on other genotypes are presented under individual trials.

Experiment 1

This experiment was conducted at Emerald in Central Queensland on a dark grey cracking clay soil during 1979. This soil had an effective depth of *c.* 70 cm and overlies weathered basalt. Treatments included irrigation (nil and full), five times of planting (T_1, 2 March; T_2, 21 March; T_3, 23 April; T_4, 23 May; T_5, 11 July), and six genotypes. There were two replicates. Irrigation was applied by flooding so as to maintain the soil in the wetter half of the available range. This involved six flood irrigations in T_1, five in T_2 and T_3, and four in T_4 and T_5. The genotypes were all WW15 derivatives, but with rates of development decreasing in the following order: Banks, Condor, WW15 (unregistered), Cook, Oxley and QT4144 (unregistered). The leaf area index (LAI) at this site was estimated from the measured total dry weight and leaf area to total dry weight ratio from the appropriate irrigation treatment in experiment 2. Available soil water at emergence in the dryland trials was in order of planting 132, 136, 117, 109, 111 mm. Leaf and stem rust control was by monthly sprayings of all treatments with the systemic fungicides butyl triazole and triadimefon.

Experiment 2

This experiment was conducted at Biloela in the Dawson–Callide region in 1979, and was identical in design and treatments to experiment 1 except that the irrigation was applied by spray, and plant and soil samples (to 120 cm) were taken monthly through the growing periods. The planting dates were 9 March, 2 April, 9 May, 5 June and 3 July. The crops in the dryland part of this trial were severely damaged by birds, mice and inadvertent flooding and the results are not presented. Rust control was carried out as for the Emerald trial.

Experiment 3

This was conducted during 1974 at Miles in the Western Downs on a cracking black earth soil. There were five times of planting (16 April, 18 May, 26 June, 8 August, 18 September) and five genotypes (Timgalen, Gamut, Tarsa and the unregistered lines WW15 and WW33). WW33 is a long-season (slow maturing) wheat derived from WW15 and the others are older Australian cultivars. There were four replicates. Soil water was measured gravimetrically to 120 cm and plant dry weight, leaf area and yield components, where appropriate, were determined from two-row quadrats (1 m long) cut at 3-week intervals throughout the growth period. No stem rust was found in this trial. A slight amount of leaf rust occurred on WW33 in the last planting. Available soil water at emergence was in order of planting 42, 118, 105, 101, 104 mm.

Experiment 4

This dryland trial was conducted at Kingsthorpe on the Darling Downs during 1974 on a black earth of the Waco series. The design, treatments and data collected were as for experiment 3 except that the planting times were 4 April, 18 May, 15 June, 27 August and 28 September. The trial was sprayed with Mancozeb after rain events and no rust was found in any treatment. Available soil water at emergence was in order of planting 172, 194, 185, 201, 188 mm.

Experiment 5

This was conducted at Toowoomba on a krasnozem soil in both 1977 and 1978. The 1977 experiment was fully spray-irrigated at 2-week intervals. The 1978 wheat-growing season had exceptionally high and frequent rainfall and provided a water regimen equivalent to that of an irrigated trial and so the data from the 2 years are presented jointly. Only two genotypes, WW15 and Oxley, were common to the other experiments and they were sown on 20 June, 4 July, 18 July in 1977, and 3 July and 14 July in 1978. There were four replicates. Soil water change was monitored by the neutron scatter technique. Rust was controlled by spraying Mancozeb at fortnightly intervals. Slight rust infection occurred in the last planting well after the soft-dough stage had been reached by all genotypes.

Results

Recordings of mean daily temperature, mean daily class 'A' pan evaporation, rainfall and frost occurrence for the years in which the experiments were conducted at Emerald, Biloela, Miles and Kingsthorpe are shown in Fig. 1. After an early dry period Miles and Kingsthorpe both received above-average rainfall during the growing season, whereas the northern sites (Emerald, Biloela) received little rain apart from a 70 mm fall in April at Emerald. This April rain, whilst important for the crops growing at that time, had little effect on the water status of the fallow. Frost occurrence also varied widely between sites, with Emerald and Miles experiencing no severe frosts but Biloela and Kingsthorpe many.

Plant performance and selected environmental parameters for the period around anthesis are presented for WW15 in Table 1. These show that a variation in the planting date at a site led to large changes in dry weight and LAI at anthesis, in kernel weight, and in grain yield under both fully irrigated and dryland conditions.

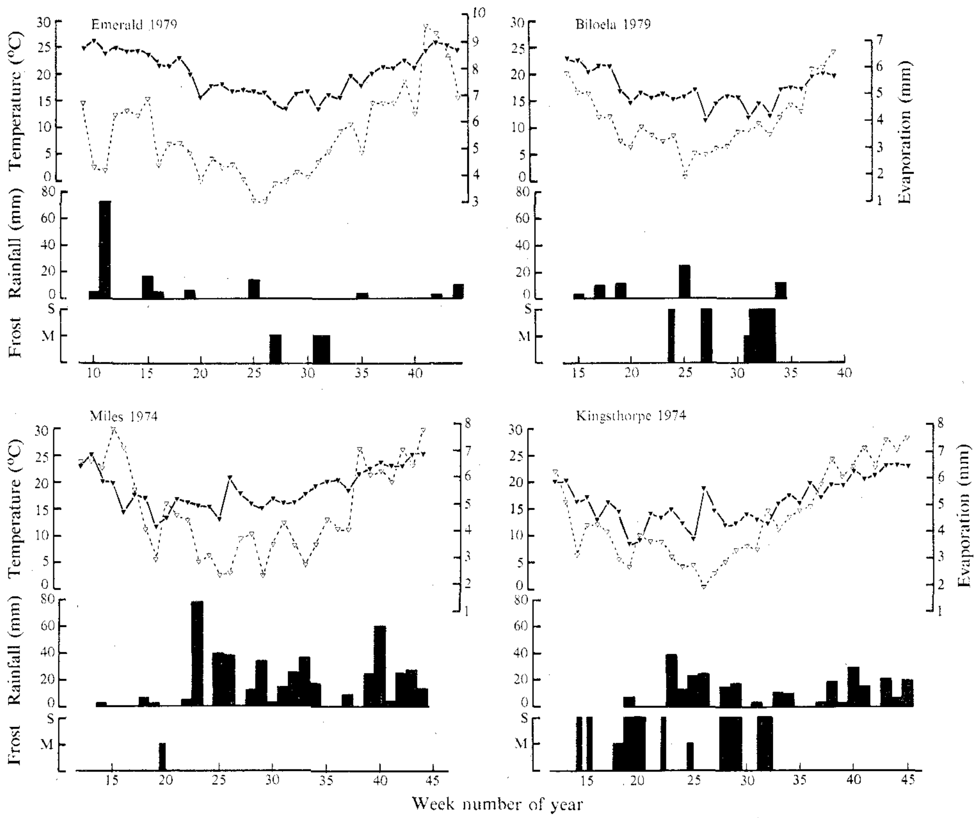

Fig. 1. Weather data for the growth period for each experiment. ▼——▼ Mean daily temperature (°C), ▽ - - - ▽ mean daily 'A' class pan evaporation (mm); histograms indicate weekly rainfall totals. Mild frost (M), minimum screen temperature +2° to 0°C; severe frost (S), minimum screen temperature <0°C.

Drought, either early and subsequently relieved (as in the first plantings at Kingsthorpe and Miles) or continued (as at Emerald), led to large reductions in grain yield, primarily in grain number per m^2 rather than in kernel weight. Similarly the yield reductions due to frost were mainly associated with reductions in grain setting. The low kernel weights at the last plantings at Emerald were due in part to stem rust, which, in spite of regular sprayings, developed at the end of September on the stem rust-susceptible genotypes WW15 and Oxley.

At Emerald, anthesis date was significantly ($P < 0{\cdot}05$) advanced by the drought (see Table 1), and this effect was consistent across genotypes (Table 2). Except for all plantings at the dryland Emerald site and the June plantings at Miles and Kingsthorpe, water use around anthesis was controlled by LAI rather than by soil water supply, according to the water use model.

Significant differences in grain yield between genotypes occurred at many planting times (Table 2), with the responses being similar at the Miles and Kingsthorpe and at the Biloela and Emerald sites. Tables 1 and 2 show that the genotypes with longer growing seasons (QT4144 and WW33) generally had a higher grain yield than the quicker genotypes at early plantings in all trials except the highly water-stressed

Table 1. Plant and environmental factors around anthesis for WW15 across sites and planting times

Planting date	Anthesis date	Dry wt at anthesis (g m^{-2})	LAI at anthesis	Grain yield (g m^{-2})	1000-kernel wt (g)	No. of grains per ear	Estimated water use[AB] (mm day^{-1})	Pan evaporation[A] (mm day^{-1})	Mean daily temp.[A] (°C)
				Experiment 1: Emerald, Irrigated					
2.iii	23.iv.79	467	2·9	223	32·5	29·3	3·8	4·9	22·2
21.iii	10.v.79	393	2·4	334	33·0	19·5[C]	3·1	4·4	18·3
23.iv	29.vi.79	540	3·3	546	31·5	31·4	2·5	3·1	15·3
23.v	8.viii.79	822	4·9	328	23·5	32·0	4·8	5·3	17·7
11.vii	12.ix.79	645	3·9	263	20·0	20·9	5·7	6·7	21·3
				Experiment 1: Emerald, Dry					
2.iii	23.iv.79	408	1·8	62	30·8	20·6	0·7[E]	4·9	22·2
21.iii	6.v.79	328	1·4	101	36·4	18·1	0·8[E]	4·6	18·2
23.iv	19.vi.79	269	1·2	181	37·9	20·4	0·8[E]	3·2	16·8
23.v	1.viii.79	413	1·8	202	31·8	28·4	0·8[E]	4·7	15·7
11.vii	8.ix.79	180	0·8	72[D]	20·1[D]	11·0	0·4[E]	6·5	20·7
				Experiment 2: Biloela, Irrigated					
9.iii	21.v.79	380	2·7	376	29·6	26·0	2·6	3·5	17·6
2.iv	20.vi.79	600	2·8	258[C]	26·8	17·0[C]	2·4	2·9	15·5
9.v	22.vii.79	515	3·2	486	38·5	31·9	2·7	3·4	15·5
5.vi	28.viii.79	520	3·1	303	25·7	25·4	3·5	4·5	19·8
3.vii	17.ix.79	500	3·0	283	24·7	30·6	4·4	5·7	21·7
				Experiment 3: Miles					
16.iv	10.vii.74	290	0·8	164	34·3	12·7	1·0	2·9	15·0
18.v	5.ix.74	800	3·4	501	36·8	31·9	3·0	3·7	16·2
26.vi	26.ix.74	800	3·3	358	30·3	24·0	3·2[E]	4·2	17·9
8.viii	25.x.74	650	1·3	298	28·0	23·6	3·2[E]	6·9	20·6
18.ix	18.xi.74	311	0·6	128	24·4	20·0	1·7	6·8	23·3
				Experiment 4: Kingsthorpe					
12.iv	3.viii.74	510	1·7	171[C]	29·3	14·3[C]	1·4	2·4	14·0
18.v	16.ix.74	942	3·3	471	39·0	28·1	2·4	2·9	15·4
25.vi	1.x.74	850	2·4	317	35·2	33·2	3·4[E]	5·4	18·0
27.viii	8.xi.74	505	1·5	180	27·7	25·4	3·7	7·0	21·6
28.ix	2.xii.74	480	0·5	150	28·1	20·9	1·7	7·6	23·4
				Experiment 5: Toowoomba					
20.vi	2.x.77	780	5·6	628	34·4	37·2	3·8	4·0	14·6
3.vii	9.x.78	865	5·6	567	32·5	34·9	3·9	4·1	15·4
4.vii	7.x.77	800	5·6	468	34·6	37·9	4·0	4·2	13·9
18.vii	13.x.77	600	4·8	529	37·4	31·0	3·8	4·1	16·9
24.vii	15.x.78	780	4·6	417	30·0	30·0	4·3	4·8	16·8

[A] Estimated over the period anthesis ± 10 days.
[B] Estimated by water use equation 1 or 2 (see text).
[C] Frosted at anthesis.
[D] Late stem rust.
[E] Controlled by soil water status.

dryland Emerald treatments. High yields were associated with high total dry weights and LAI values at anthesis. These yield differences ceased or were reversed at later plantings when the differences between the quicker and slower genotypes in anthesis date, and often in total dry weight and LAI at anthesis were reduced. The non-semidwarf genotype group, exemplified by cv. Timgalen in Table 2, generally yielded less than the WW15-derived genotypes at most planting times. Under the dryland treatments that produced high water stress at Emerald the slow-maturing genotype QT4144 often yielded significantly less than the quicker genotypes in spite of higher dry weights at anthesis. These differences were associated with the lower available soil water at anthesis. Since there were no significant differences with time of sowing in the available soil water at anthesis for the dryland Emerald treatments, only the average mean water use of 12 mm for the quicker genotypes and 2 mm for the slow

Table 2. The major grain yield differences in the Emerald and Miles experiments

Genotype	Planting date	Anthesis date	Dry wt at anthesis ($g\ m^{-2}$)	LAI at anthesis	Grain yield ($g\ m^{-2}$)	10000-kernel wt (g)	Head No. (m^{-2})	Estimated water use ($mm\ day^{-1}$)	Mean pan evaporation[A] ($mm\ day^{-1}$)	Mean daily temp.[A] (°C)
				Experiment 1: Emerald, Irrigated (1979)						
Banks	2.iii	22.iv	357	2·3[B]	165	36·3	451	3·4	5·0	22·1
QT4144	2.iii	14.v	473	3·0	295	44·2	357	3·4	4·4	17·7
Banks	21.iii	6.v	198	1·4	237	37·6	339	2·3	4·6	18·2
QT4144	21.iii	16.vi	478	3·0	414	37·4	344	2·6	3·3	16·6
Banks	23.iv	7.vii	682	4·4	512	27·2	613	3·1	3·5	15·8
QT4144	23.iv	8.viii	990	6·4	477	35·4	519	4·8	5·0	16·0
Banks	23.v	9.viii	773	4·7	407	30·7	479	4·4	4·9	15·8
QT4144	23.v	28.viii	963	6·2	350	32·4	408	5·9	6·2	20·5
Banks	11.vii	12.ix	593	3·8	338	27·0	525	5·7	6·7	21·3
QT4144	11.vii	24.ix	723	4·6	338	27·3	576	6·9	8·0	22·4
				Experiment 1: Emerald, Dry (1979)						
Banks	2.iii	22.iv	394	1·7	73	30·8	488	0·7[C]	5·0	22·1
QT4144	2.iii	11.v	470	2·1	25	33·6	263	0·1[C]	4·4	18·0
Banks	21.iii	4.v	126	0·6	121	31·0	296	0·8[C]	4·8	18·7
QT4144	21.iii	4.vi	184	0·8	29	31·7	201	0·1[C]	3·6	17·5
Banks	23.iv	15.vi	273	1·2	153	38·8	320	0·3[C]	3·4	16·7
QT4144	23.iv	16.vii	280	1·3	71	31·6	204	0·1[C]	4·3	18·2
Banks	23.v	30.vii	334	1·5	229	27·9	378	0·8[C]	4·5	15·7
QT4144	23.v	18.viii	448	2·0	139	30·4	379	0·1[C]	5·5	18·0
Banks	11.vi	8.ix	195	0·9	175	26·4	183	0·4[C]	6·5	20·5
QT4144	11.vi	17.ix	267	1·2	90	25·6	346	0·1[C]	7·5	23·0
l.s.d. ($P = 0·05$)[D]			150	0·4	87	4·3	128	0·5		
				Experiment 2: Miles, Dry (1974)						
WW33	16.iv	5.ix	911	4·7	458	27·2	558	3·3	3·7	16·2
Timgalen	16.iv	26.ix	364	1·5	359	33·1	637	1·5	2·8	14·7
WW33	18.v	26.ix	1026	4·0	371	30·0	458	3·2[C]	4·2	17·9
Timgalen	18.v	5.ix	800	3·3	312	36·9	450	3·0	3·7	16·2
WW33	26.vi	10.x	806	2·9	192	19·5	422	3·3[C]	5·5	20·1
Timgalen	26.vi	26.ix	800	4·2	313	30·9	420	3·2	4·2	17·9
WW33	8.viii	22.ix	670	0·3	72	23·5	347	1·0	7·0	23·4
Timgalen	8.viii	27.x	573	1·2	165	26·5	360	3·2	6·9	20·5
Timgalen	18.ix	29.xi	300	0·5	80	21·1	152	1·5	6·9	23·7
l.s.d. ($P = 0·05$)			137	0·7	69	3·0	109	0·7		

[A] Estimated over the period anthesis ± 10 days.
[B] LAI and water use of irrigated trial (Emerald) estimated by LAI = 0·006 × TDW, and water use = 1 − exp(−0·5 × LAI) × E_0.
[C] Water use controlled by soil water status rather than leaf area according to the function used.
[D] l.s.d. refers only to dryland treatments.

genotypes were used in subsequent calculations. The lack of significant differences in soil water status with time of planting was due to the shallow soil and the large effect of small variations in this depth when nearly all the available water had been used prior to measurement.

The yield of each genotype relative to the maximum yield of the site is shown for various genotypes and sites as a function of anthesis date in Fig. 2. Maximum grain production tended to occur during frost-free periods and from crops with anthesis dates in midwinter. Yields declined almost linearly as anthesis dates departed

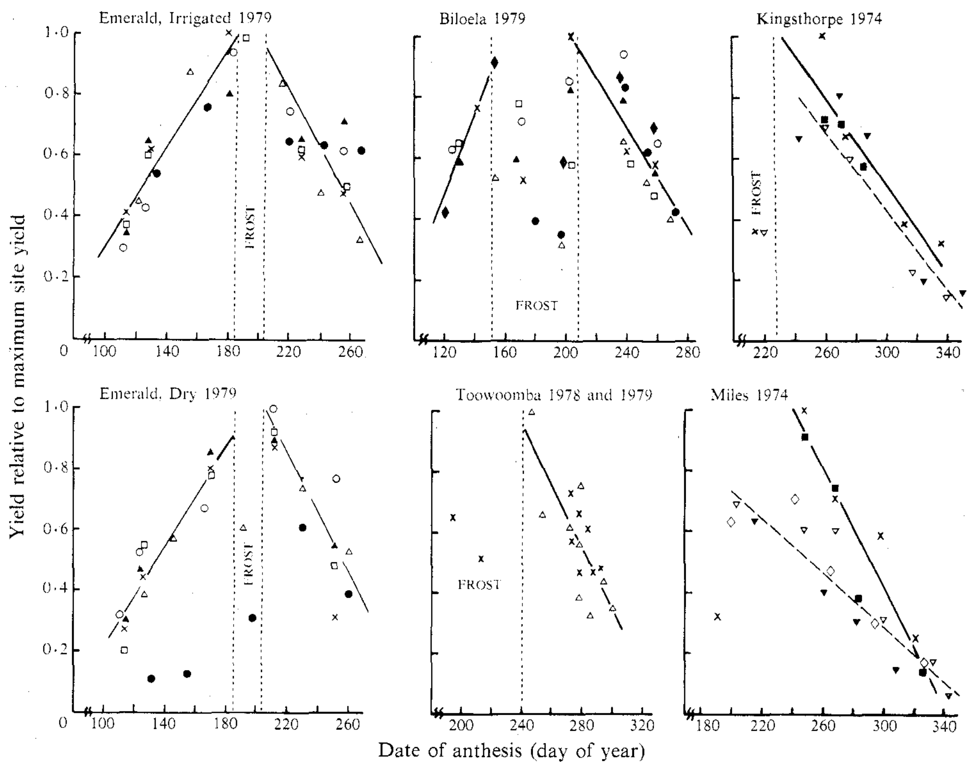

Fig. 2. Influence of date of anthesis on the relative yield of wheat genotypes varying in developmental rate. Semidwarf (——): × WW15; ■ WW33; △ Oxley; ● 4144; ♦ 7605; □ Condor; ○ Banks; △ Cook; non-semidwarf (– – –): ▼ Tarsa; ▽ Timgalen; ◊ Gamut.

Table 3. Coefficients of correlation between plant and environmental variables around anthesis in the semidwarf wheats (n = 112)

	Total dry wt (g m^{-2})	LAI	1000-kernel wt (g)	Grain No. (m^{-2})	Grain yield (g m^{-2})
Total dry weight (g m^{-2})[A]	—	0·792	0·160	0·663	0·668
LAI[A]	0·792	—	0·170	0·705	0·728
Available soil water (mm)[A]	0·312	0·600	0·182	0·602	0·609
Daily temperature (°C)[B]	−0·355	−0·336	−0·454	−0·481	−0·590
Pan evaporation (E_0) (mm day^{-1})[B]	−0·140	−0·160	−0·545	−0·334	−0·463
Transpiration (mm day^{-1})[B]	0·577	0·746	−0·033	0·712	0·610
Available soil water/E_0[C]	0·523	0·412	0·110	0·747	0·749
Yield index[D]	0·760	0·804	0·130	0·902	0·895

[A] Measured at anthesis (A).
[B] Mean values for the period anthesis ±10 days.
[C] Approximates Nix and Fitzpatrick (1969) index.
[D] Yield index = (transpiration/E_0)/(mean daily temperature over the period anthesis ±10 days).

from midwinter. The yield reductions due to frosts around anthesis were sometimes large, equalling the reduction from a substantial delay in anthesis date. At Miles the anthesis of WW33 generally coincided with that of WW15 planted one month later and the grain yields from these two genotypes were similar for common anthesis dates under those conditions where soil water was recharged by rainfall just prior to anthesis. The remaining variation in yield between these two genotypes was a function of their relative leaf area index and total dry weight at anthesis.

The correlation coefficients between plant and environmental factors for the semidwarf wheats, with the exclusion of the frosted crops, are presented in Table 3 which includes variation due to site, sowing date, genotype and irrigation. Variation in grain yield was primarily associated with variation in grain number, together with a much smaller positive effect of kernel weight. The major factors positively correlated with grain number were plant dry weight and its associated LAI at anthesis, and soil water status. Both pan evaporation and daily mean temperature in the period anthesis ± 10 days were negatively associated with grain number and yield and were

Table 4. Significant multiple regression coefficients relating yield to plant environmental factors for different genotypes

YI, yield index (see Table 3)

Genotype	Intercept	YI	$(YI)^2$	LAI	n	R^2
Grain yield ($g\ m^{-2}$)						
WW15	146	2507	121719	−37	28	0·923
Oxley	135	4061	65482	−20	23	0·780
Cook	118	9820	—	−28	14	0·891
Banks	97	6269	—	—	14	0·827
Condor	116	3766	65756	−14	17	0·802
QT4144	86	6132	—	—	9	0·951
WW33	90	—	118309	—	7	0·934
Combined WW derivatives (semidwarf)	112	3962	68432	−20	112	0·830
Combined non-semidwarf genotypes	148	2833	46291	—	33	0·741
Grain weight (g per 1000 grains) combined for all genotypes $= 52\cdot0 - 2\cdot09E_0 - 0\cdot45T_m + 0\cdot74\mathrm{LAI}$					145	0·430

the only two factors with any significant correlation with kernel weight. In explaining variation in grain yield there was little advantage in considering water use, estimated from equation 1 or 2, rather than soil water status, unless the reciprocal of pan evaporation and mean daily temperature were considered also, and incorporated into a yield index (YI). With this index a much higher correlation was obtained with grain yield ($r = 0\cdot895$) and grain number ($r = 0\cdot902$).

Multiple linear regression analysis by progressive deletion of best predictors (Table 4) showed that grain yield of each genotype, excluding frosted crops, was associated with the yield index, or its square, together with LAI at anthesis. Tests of parallelism and of the intercept for these regressions showed no significant differences within either the genotype group based on WW15 or the non-semidwarf types, but there were significant differences between these two groups. The replacement of the intercept in the combined semidwarf yield equation with the variable function of total dry weight per unit area (TDW) gave

$$13\cdot0+0\cdot496\mathrm{TDW}-0\cdot00041(\mathrm{TDW})^2.$$

Whilst leading only to a slight increase in total explained variation ($r^2 = 0\cdot84$), the replacement greatly improved the prediction of a subset of individual genotypes with yields below $1 \cdot 2$ t ha^{-1}, which would otherwise have fallen to $r^2 = 0 \cdot 72$. Overall, 84% of the total yield variation due to site, treatment and genotype was explained by these regressions within the semi-dwarf group, whereas the simple linear regressions, $Y = -13 \cdot 7 + 7437\mathrm{YI}$ and $31 \cdot 0 + 4778\mathrm{YI}$, explained $80 \cdot 1$ and $65 \cdot 4$% of the semidwarf and non-semidwarf yield variation respectively. Most of the significant interactions between time of planting and genotype (Tables 1 and 2) can be regenerated by applying these equations, especially if the individual genotype regressions rather than the overall regression for WW15 derivatives are used. There were no significant differences between any genotypes in the relatively low association found between 1000-kernel weight and measured plant and environmental factors.

Discussion

Because of the low and erratic winter rainfall in the Queensland wheat belt, there are limited opportunities to establish wheat crops. It is important to know the type of varietal development best suited to exploit these limited opportunities and the risks and benefits associated with such planting times. The results from these experiments suggest that the anthesis date and the prevailing plant and environmental conditions around that date determine grain yield. The general trend in grain yield, in the absence of frost damage, was to decrease almost linearly as the anthesis date departed from the optimal midwinter period. This decline, averaging $1 \cdot 2$% per day, was associated with increasing daily mean temperature and evaporative demands in both fully irrigated and dryland trials.

Under high rainfall or irrigated conditions, early plantings designed so that the plants reach anthesis before the frost period in regions such as Emerald, appear to require relatively long season genotypes to provide the dry weight and LAI required to maximize yield potential. The value of using such genotypes, which reach anthesis after the frost period, depends upon the opposing effects of the large potential leaf area development and the extra water use involved prior to anthesis. In the Miles experiment the long season genotype reached anthesis on a similar date to WW15 planted a month later, but there were no differences in grain yield because of soil water recharge just prior to anthesis and leaf area index approaching the asymptote with yield. In the dryland Emerald treatment, however, the long season wheat QT4144 yielded significantly less than the quicker genotypes because its greater leaf area meant that soil water was exhausted before anthesis and so transpiration was actually reduced relative to that of the quicker genotypes.

The plant and environmental factors can be integrated by measuring or predicting the growth potential around anthesis. de Wit (1958) and van Keulen (1975) have shown that dry matter (DM) was related to transpiration thus:

$$\mathrm{DM} = mT/E_0,$$

where T is transpiration (mm), E_0 is average free water evaporation (mm day^{-1}) and m is a crop factor with similar dimensions to DM. Hanks (1974) has shown that this equation, applied over a set period, is well related to plant growth and grain yield in sorghum and maize. Similarly Rasmussen and Hanks (1978) found that relative grain yield in wheat was well related to (actual/potential transpiration)$^{0 \cdot 25}$ for each of four growth stages. They used a fixed potential transpiration function with development rather than with measured TDW or LAI at anthesis. In the present study the use of measured TDW and/or LAI together with the soil water status to predict transpiration around anthesis provides an integrated measure of prior environmental conditions and thus appears to remove the need for measured water use in the early growth phases or potential yield.

A rapid change from severe to non-stress conditions by a heavy rain event just prior to anthesis, as occurred in the first Miles planting, suggests a higher yield, according to yield indices based on soil water status such as that presented by Nix and Fitzpatrick (1969), than occurs because it fails to consider the previous stress history effects on TDW and LAI. The use of water use, or preferably transpiration, rather than soil water status, over the period around anthesis overcomes such problems by integrating the effects of TDW and its associated LAI and soil water status and can be used for both dryland and irrigated conditions. In the present experiments, 22 of the 30 plantings were limited by LAI, rather than soil water status, according to the transpiration model used.

The use of a yield index constructed from plant and environmental variables only in the period surrounding anthesis implies that factors outside this period are either unimportant or highly correlated with the level of the variables at anthesis. For example, leaf area duration (LAD) has often been found to be highly correlated with grain yield (Fischer and Kohn 1966) but, owing to the linear decline in LAI from flowering to maturity, LAD is also highly correlated with LAI at anthesis. The effect of temperature on the duration of the period from anthesis to maturity could explain its significance in the yield index presented. Alternatively the temperature term could indicate that the index should relate to a temperature-controlled, phenological period, rather than to a set number of days. The major factor, however, is that the yield index so derived is highly correlated with the growth potential which is highly buffered against sudden changes due to the control of transpiration by either soil water or leaf area, whichever is the most limiting at a given time.

There were significant genotype differences between the yield regressions for the WW15-derived and non-semidwarf groups of genotypes, due almost entirely to their differing grain-setting abilities at a given level of the yield index. The higher grain-setting abilities of WW15 compared with the non-semidwarf genotypes have been previously reported (Syme 1972). Comparisons of either the intercepts or slopes of the relationships within a group showed no significant differences, suggesting that the plant breeders have been successful in transferring the high grain-setting ability of WW15 to its offspring. The large differences in the yield of genotypes of differing development, within a group and from a given sowing time, were primarily due to the interactions between growth duration (and hence dry weight and LAI development), water use, and the temperature and evaporative demand conditions around anthesis.

The results from this limited set of experiments suggests that, in these regions of low frost risk, a change in current planting times should be made to bring anthesis time into the higher yield potential midwinter period. It also suggests that the grain yield variation from a given anthesis period is highly correlated with the growth potential around anthesis, which is largely controlled by the transpiration and evaporation demand at that time.

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References

Al-Khafaf, S., Wierenga, P. J., and Williams, B. C. (1978). Evaporative flux from irrigated cotton as related to leaf area index, soil water and evaporative demand. *Agron. J.* **70**, 912–17.

Berndt, R. D., and White, B. J. (1976). A simulation-based evaluation of three cropping systems on cracking-clay soils in a summer rainfall environment. *Agric. Meteorol.* **16**, 211–29.

Fischer, R. A., and Kohn, G. D. (1966). The relationship of grain yield to vegetative growth and post-flowering leaf area in the wheat crop under conditions of limited soil moisture. *Aust. J. Agric. Res.* **17**, 281–95.

Hanks, R. J. (1974). Model for predicting plant yield as influenced by water use. *Agron. J.* **65**, 660–5.

Johns, G. G., and Smith, R. C. G. (1975). Accuracy of soil water budgets based on a range of relationships for the influence of soil water availability on actual water use. *Aust. J. Agric. Res.* **26**, 871–83.

van Keulen, H. (1975). 'Simulation of Water Use and Herbage Growth in Arid Regions.' (Pudoc: Wageningen, The Netherlands.)

Linacre, E. T. (1973). A simpler empirical expression for actual evapo-transpiration rates—a discussion. *Agric. Meteorol.* **11**, 451–2.

Nix, H. A., and Fitzpatrick, E. A. (1969). An index of crop water stress related to wheat and grain sorghum yields. *Agric. Meteorol.* **6**, 321–37.

Rasmussen, V. P., and Hanks, R. J. (1978). Spring wheat yield model for limited water conditions. *Agron. J.* **70**, 940–4.

Syme, J. R. (1972). Features of high yielding wheats grown at two seed rates and two nitrogen levels. *Aust. J. Exp. Agric. Anim. Husb.* **12**, 165–70.

Waring, S. A., Fox, W. E., and Teakle, L. J. H. (1958). Fertility investigations on the black earth wheatlands of the Darling Downs, Queensland. II. Moisture and evapotranspiration in relation to the wheat crop. *Aust. J. Agric. Res.* **9**, 717–29.

de Wit, C. T. (1958). Transportation and crop yields. Versl. Landbouwkd. Onderz. [Agric. Res. Rep.] 64·6. (Pudoc: Wageningen, The Netherlands.)

Woodruff, D. R. (1975). Decision making for wheat growers in Queensland. Qld Dept. Prim. Ind. Agric. Branch Tech. Bull. No. 16.

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