Genotype, Sowing Date and Plant Spacing Influence on High-yielding Irrigated Wheat in Southern New South Wales. III*
Potential Yields and Optimum Flowering Dates

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Abstract

Experiments were undertaken at Griffith, N.S.W., using a range of genotypes, sowing dates and plant spacing to identify management strategies and genotypes that would increase irrigated wheat yields and minimize lodging risk. Results are used in this paper in an analysis of potential yield and optimum anthesis date, as influenced by temperature, irradiance, sowing date and genotype.

Lodging duration was used to predict potential yields in absence of lodging from the lodging-affected yields in the study. Lodging duration between 7 days after mid-anthesis and maturity was found to best explain early and late lodging effects on yield. Yield reductions due to lodging were up to 45%. Predicted potential yields (Y_p) were 800–950 g/m^2 and the end of the optimum anthesis period varied from year to year. Average temperature (T, °C) and total irradiance (ΣR, MJ/m^2) for a pre-anthesis period of 500°C days (>3°C) or a maximum of 60 days explained 61% of the variation in Y_p: $Y_p = 981 - 53 \cdot 4T + 0 \cdot 51 \Sigma R$ (g/m^2).

Using historical weather data and frost risk restrictions indicated an optimum anthesis period between 22 September and 10 October when average predicted yields were reasonably stable. Flowering after mid-October caused reductions in average predicted yield of 70 g/m^2 or 11% per 1-week delay in anthesis. Kernel weights decreased by 5% per 1°C above 14°C, but this decrease was also associated with increased kernel numbers. High-yields under irrigation can only be achieved consistently and efficiently with lodging resistant (short, stiff stems) or avoiding (early maturing) genotypes. Very early maturing types for late sowing dates are currently not commercially available. Adjusted management practices (e.g. relatively late sowing) and lower target yields are recommended for current lodging susceptible varieties.

Introduction

Our first paper in this series (Stapper and Fischer 1990*a*) describes reasons for examining the potential, given optimal management, of irrigated wheat in southern New South Wales. Thus wheat crops were studied at Griffith between 1983 and 1985 using many sowing dates and genotypes, with water and nitrogen non-limiting and good control of diseases and weeds. The overall aim of the experiments was to identify better management practices and genotypes for high-yielding conditions, through improving our understanding of development and growth of irrigated wheat. Our first two papers describe phasic development, canopy growth and spike production (Part I, Stapper and Fischer 1990*a*), and growth, yield and nitrogen use (Part II, Stapper and Fischer 1990*b*) of wheat crops in this study. In this paper we assess the general effects of climate and genotype on potential yields and optimum anthesis date after quantifying lodging damage, and we conclude with a description of an ideotype for irrigated wheat.

The determination of yield potential in wheat has been the subject of many field studies (e.g. Midmore *et al.* 1982, 1984) and simulation studies (e.g. Stapper and Harris 1989). Yield formation has also been studied in controlled environments (e.g. Evans 1978), and

through manipulation of field crops using shading (Fischer 1975) or heating and cooling (Fischer and Maurer 1976). Temperature and irradiance become the most important factors determining potential yield when water and nitrogen are managed optimally. Temperature and irradiance influence plant processes differently, but their combined effect can be usefully described by the photothermal quotient (PTQ, mean solar irradiance divided by mean temperature), which represents the amount of growth per unit development time (Nix 1976). Midmore *et al.* (1984) and Fischer (1985) showed that kernel number was associated with the PTQ over the 30 days preceding anthesis. Major factors which can reduce wheat yields under such management are lodging and frost. Genetic differences in, for example, maturity and stature cause these factors to be expressed differently for different sowing dates and seasons.

Reductions in yield with delayed sowing under conditions where water and nitrogen are non-limiting have been attributed to reduced kernel numbers caused by higher pre-anthesis temperatures (Fischer and Maurer 1976), and to reduced kernel weights caused by higher post-anthesis temperatures (Sofield *et al.* 1977; McDonald *et al.* 1983) even though in each case irradiance levels also increased. Early anthesis date is therefore clearly important for high yields. However, flowering too early in the spring increases risk of frost damage thereby reducing kernel number.

Lodging is a major problem for wheat production under irrigation (Fischer and Wall 1976; Eck 1988; Stapper and Fischer 1990*b*). Yield reductions of up to 50% can occur, and grain quality may be reduced by sprouting (Fischer and Stapper 1987). Lodging risk increases with increased dry weight at anthesis and for taller crops, both associated with the duration from sowing to anthesis (Stapper and Fischer 1990*a*, 1990*b*). Genotypic

Table 1. Summary of genotypes and sowing dates used from the 1983–85 experiments at Griffith, N.S.W.

Experiment 1

Genotypes: Yecora (1)[A], Egret (4), WW33G (5), UQ189 (6s)
Sowing dates: 14 April (S1), 12 May (S2), 17 June (S3), 11 August (S4) 1983

Experiment 2

Genotypes: Yecora (1), Egret (4), WW33G (5), UQ189 (6s), Q19 (2), Dua (2), Q134 (2), Takari (2), Q206 (2), Q143 (2), WW425 (3), Hartog (3), M3301 (3), T12 (3), Millewa (3), Corella (3), SUN64M (3), Oxley (4), Grebe (4), Bindawarra (4), Osprey (5), Quarrion (5), Harrier (5s), AT-12 (6)
Sowing dates: 19 May (S6), 3 July (S7) 1984

Experiment 4

Genotypes: Yecora (1), Bindawarra (4)
Sowing dates: 19 May (S6), 3 July (S7), 27 August (S8) 1984

Experiment 5

Genotypes: Yecora (1), Q19 (2), Dua (2), Q134 (2), Fiserect-3 (2), Takari (2), Q206 (2), Q143 (2), Vulcan (3), Currency (3), Skua (3), WW425 (3), Millewa (3), Corella (3), Osprey (5), Harrier (5s)
Sowing date: 12 June (S10) 1985

Experiment 6a

Genotype: Osprey (5)
Sowing date: 22 April (S9) 1985

Experiment 6b

Genotypes: Yecora (1), Egret (4)
Sowing date: 12 June (S10) 1985

[A]Maturity group (Stapper and Fischer 1990*a*): 1, very early; 2, early; 3, medium; 4, medium late; 5, late; 6, very late; S, photoperiod sensitive.

differences in height, stem stiffness, angle of roots and shoot density (i.e. light penetration) may reduce lodging risk (Pinthus 1973). Yield reductions depend on the timing and severity of lodging (Fischer and Stapper 1987), but there is presently no simple relationship to calculate damage from lodging.

Materials and Methods

Details of the location, weather, experiments and genotypes are given in Part I (Stapper and Fischer 1990a). Table 1 presents a summary of the experiments used in this paper. Experiment 6 consisted of only lodging-protected treatments of lodging studies at Griffith described by Fischer and Stapper (1987). Yield reduction caused by lodging was quantified here using all treatments in that study. This is to allow estimation of maximum yields in the absence of lodging from measured lodging scores and grain yields for Experiments 1, 2 and 5. These corrected yields were used in regression analysis to evaluate effects of temperature and irradiance on potential yield, and to determine optimum flowering dates. All yields refer to oven-dry weights. Lodging was scored visually as follows:

$$\text{lodging score} = \% \text{ of plot area lodged} \times \text{angle of lodging}/90,$$

where the angle refers to the angle of the shoots with the vertical (Fischer and Stapper 1987).

Degree-days were calculated by accumulating daily mean temperatures after subtracting a base temperature of 3°C unless stated otherwise. The combined variation in irradiance and temperature was expressed with the photothermal quotient (PTQ) and was calculated for any period as mean daily total irradiance divided by mean daily degree-days (MJ m^{-2} (°C days)$^{-1}$).

Results and Discussion

Lodging Duration and Yield Reductions

An objective assessment of lodging effects on grain yield was required to estimate the non-lodged equivalent or potential yields in the present studies. Lodging scores and yields with and without lodging were available from detailed lodging studies at Griffith in 1985 (Fischer and Stapper 1987). The genotypes used in those lodging studies were Yecora, Egret and early sown Osprey and thus representative of the genetic material in the present studies (see Table 4 in Stapper and Fischer 1990a). The controls (no lodging; growing through mesh
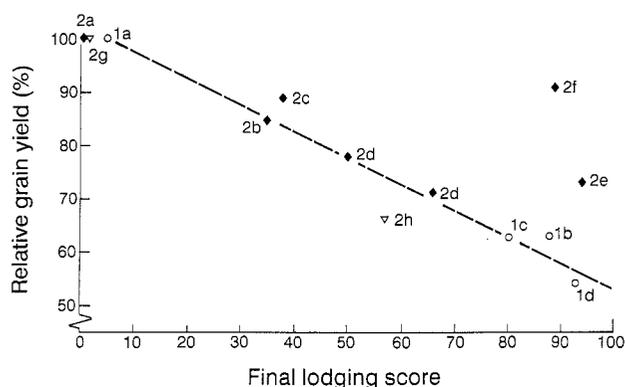
Fig. 1. Relative grain yield, the ratio of actual and potential grain yield, as a function of lodging score at maturity for a lodging study at Griffith in 1985 using Yecora (♦), Egret (▽) and Osprey (○). The broken line is the relationship between lodging score at stage DC78 and relative grain yield showing a 1% yield reduction for each 2% increase in lodging. 1a, 2a and 2g — lodging controlled (Expt 6). 1b, 2b and 2h — natural lodging at DC65 − 80d, +14d and −5d, respectively. 2c — artificial lodging at DC65 − 9d. 2d — artificial lodging at DC65 + 6d. 2e — artificial lodging at DC65 + 21d. 2f — artificial lodging at DC65 + 35d.

wire) were used in the present studies (Experiment 6*a, b*) as a reference for high yields in 1985.

Final lodging scores were not useful in describing lodging effects on yield relative to maximum yield (Fig. 1) as the score did not account for the timing of lodging. Timing is important, as the greatest effect on yield reported by Fischer and Stapper (1987) occurred in the first 20 days after anthesis, with lodging prior to anthesis being relatively less deleterious because of the tendency of the crop to right itself. Lodging score at DC78 (late milk; about 50% grain weight) in Experiment 6 was a good indicator of the yield reduction caused by early lodging, with a 1% yield loss for each 2% increase in the lodging score at DC78 (broken line, Fig. 1). The effects of lodging after DC78, however, could not be quantified in this way. Lodging durations were therefore used instead.

Fig. 2 gives an example of lodging score patterns in S6 Experiment 2 for the four standard genotypes. Lodging durations were calculated from the lodging scores by
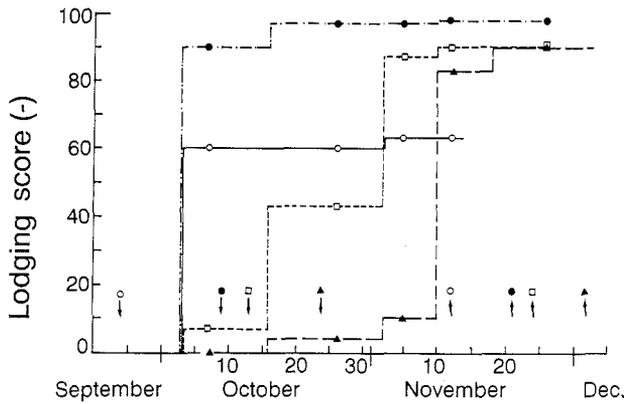

Fig. 2. Lodging scores as a function of time for Yecora (○), Egret (●), WW33G (□) and UQ189 (▲) in S6 Expt 2. Dates of DC65 (↓) and DC86 (↑) are shown for each genotype.
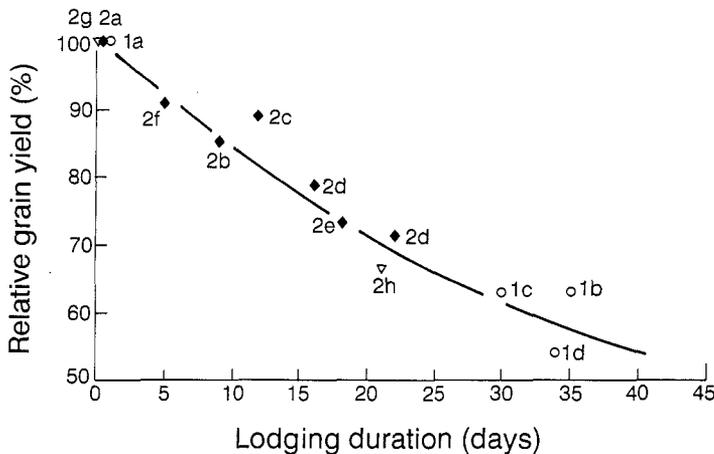

Fig. 3. Relative grain yield as a function of lodging duration between DC65 + 7 and DC86 for the lodging study at Griffith in 1985. See Fig. 1 for the legend.

summation of daily lodging scores (divided by 100) between a starting point and maturity (DC86). To find the appropriate starting point for the summations we considered: commencement of lodging, DC65 (mid-anthesis), DC65 + 5 (plus 5 days), DC65 + 7 and DC65 + 9. Seven days after DC65, which roughly coincides with the start of rapid grain-filling (DC70·7), was the best starting point to calculate lodging duration (L_d) as it gave the best fit (Fig. 3). The equation,

$$100 Y_a/Y_p = 100 - 1·71 L_d + 0·014 L_d^2 \ (\%), \tag{1}$$

gave the lowest residual error, and L_d explained 96% of the variation in relative grain yields (Y_a/Y_p), with Y_a the actual yield and Y_p the non-lodged yield. The relationship represented the three genotypes and two sowing dates well, and it was assumed to be valid as a general relationship between relative yield and lodging duration.

Lodging duration between DC65 + 7 and DC86, and yield loss were thus calculated for all genotypes in Experiments 1, 2 and 5. Table 2 summarizes lodging score, duration and yield loss for the four standard genotypes in Experiments 1 and 2. Yields for Egret were most and those for Yecora were least affected. The ranking of genotypes for lodging susceptibility based on lodging duration, and hence yield loss, was generally similar to that based on lodging score at maturity (Stapper and Fischer 1990b). Average yield losses were 12 (range 0–37%), 25 (0–42%), 15 (0–33%) and 4% (0–14%) for Experiment 1, S6 Experiment 2, S7 Experiment 2 and Experiment 5, respectively. Our yield loss estimates are based on hand harvests and farmers' lodging losses are likely to be higher because of increased harvesting losses. Lodging may also negatively affect grain quality (Fischer and Stapper 1987). Lodging therefore is a major risk when pursuing high yields under irrigation in southern New South Wales.

Table 2. Final lodging scores, lodging duration and estimated yield loss for the four standard genotypes and six sowing dates in Expts 1 and 2

		Yecora	Egret	WW33G	UQ189	Mean
	Experiment 1					
S1	Score (%)	48	90	90	73	75
	Duration (days)	4	28	23	21	19
	Yield loss (%)	7	37	32	30	26
S2	Score (%)	55	70	24	40	47
	Duration (days)	9	20	6	9	11
	Yield loss (%)	14	29	10	14	17
S3	Score (%)	0	26	13	13	13
	Duration (days)	0	6	3	4	3
	Yield loss (%)	0	10	5	7	5
S4	Score (%)	0	0	0	0	0
	Duration (days)	0	0	0	0	0
	Yield loss (%)	0	0	0	0	0
	Experiment 2					
S6	Score (%)	63	98	90	90	85
	Duration (days)	24	34	25	20	26
	Yield loss (%)	33	42	34	29	34
S7	Score (%)	29	55	25	20	32
	Duration (days)	8	20	8	9	11
	Yield loss (%)	13	29	13	14	17
	Means					
	Score (%)	33	57	40	39	42
	Duration (days)	8	18	11	11	12
	Yield loss (%)	12	24	16	16	17

Potential Yield and Anthesis Date

Predicted yields for lodging-free conditions, as calculated with equation 1 from actual yield and lodging duration, are an estimate of potential yields for the genetic material represented in this study. These predicted potential yields were correlated with measured anthesis dates to examine the importance of this variable, which is dependent on sowing date and genotype, in the determination of potential yield.

For the combined data in Experiment 1, anthesis date explained 4% and 80% of the variation in grain yield before and after the lodging correction, respectively, when excluding frost damaged Yecora in S1 (Fig. 4). There were no obvious independent effects of genotype or sowing date on the resulting relationship. The reduction in yield was 33 g/m^2 per 1-week delay in anthesis (cf. 24 g/m^2 estimated in Stapper and Fischer 1990b). The lodging correction for S6 Experiment 2 resulted in a non-significant positive correlation with anthesis date (Fig. 5). Some crops that flowered late September 1984 were affected by mild frosts on 26 and 30 September (Stapper and Fischer 1990b) and were the cause of the small positive slope. The correction for S7 yielded an anthesis date response of -117 g/m^2 per 1-week delay in anthesis ($r = -0.72$**), similar to the one found for the uncorrected yields (-113 g m^{-2} week^{-1}; Stapper and Fischer 1990b), but at a higher yield level. This late response was associated with especially cool conditions in October 1984 (Fig. 8a). Despite a negative slope, the correlation between potential yield and anthesis date for Experiment 5 in 1985 was not significant (-43 g m^{-2} week^{-1}, $r = -0.31$ns; Fig. 5). Only minor lodging occurred in that experiment and other factors (leaf diseases) had limited the yields of some genotypes. Fig. 5 also shows the results for the three lodging-protected treatments of Experiment 6 in 1985.

The pattern emerging from Fig. 5 suggests that potential yields are between 800 and 900 g/m^2 (9–10 t/ha at 12% moisture) and associated with optimum anthesis dates which varied somewhat from season to season. The optimum flowering period ceased as early as 10 September in 1983 and as late as 20 October in 1984. It is clear from the analysis that
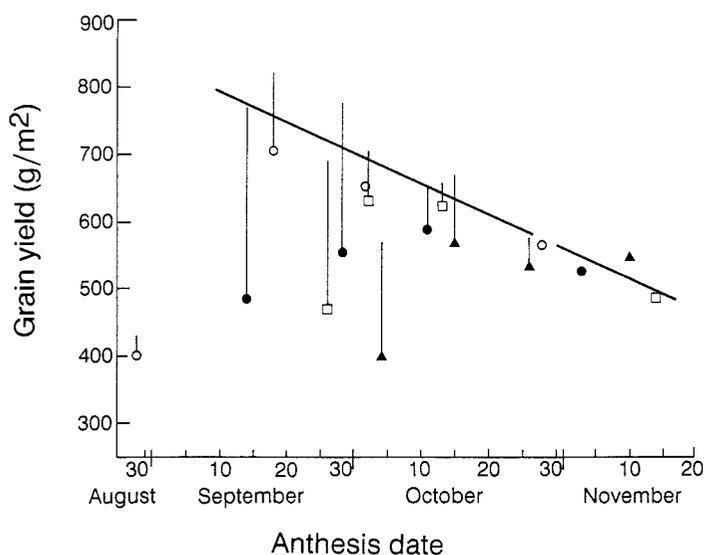

Fig. 4. Relationship between predicted potential grain yield in the absence of lodging and anthesis date for Experiment 1, 1983. The Yecora crop flowering in August was excluded from the regression because of frost damage. Vertical bars indicate the lodging correction for measured yields. ○ Yecora, ●Egret, □ WW33G, ▲ UQ189.
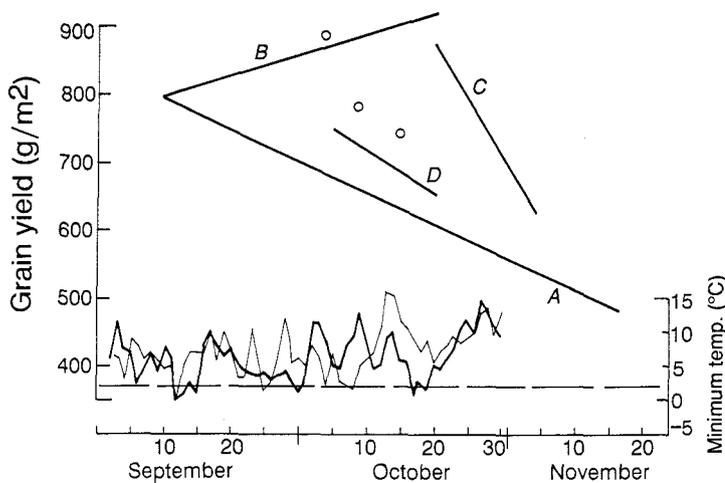
Fig. 5. Relationships between predicted potential grain yield and anthesis date for Experiment 1 (line *A*), S6 Expt 2 (*B*), S7 Expt 2 (*C*) and Expt 5 (*D*). Grain yields for the three lodging protected crops in Expt 6 are shown (○). Minimum screen temperatures during the spring are presented for 1983 (——) and 1984 (▬▬).

anthesis date is a very important factor in this environment. Conversely the sowing to anthesis duration (range: 70–190 days) and dry weight at anthesis (range: 600–1500 g/m²) do not appear to be as important as in other irrigated wheat growing areas (Woodruff and Tonks 1983; Waddington *et al.* 1986), suggesting that pre-anthesis growth is so great as to be generally not limiting (Stapper and Fischer 1990*b*). Thus climatic effects appear to dominate. Well-adapted genotypes will be found consistently above regression lines between actual yield and anthesis date (e.g. Q19, Dua and Harrier in Experiment 2). Yields from selection trials should therefore be analysed for anthesis date effects to identify such genotypes. In the next sections we will quantify the climatic parameters associated with the varying yield response to anthesis date.
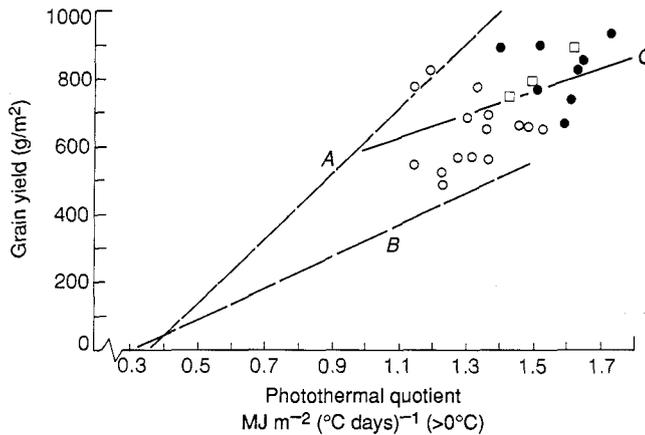
Effects of Photothermal Quotient on Yield

Fischer (1985) used PTQ calculated over 30 days preceding anthesis to successfully explain the variation, owing to sowing date and year, in kernel number per unit area for irrigated crops of Yecora in north-west Mexico. He found a similar relationship using data from an independent study by Midmore *et al.* (1984) of eight wheat varieties grown at different sowing dates, years and altitudes in Mexico. However, using the same definitions (e.g. PTQ calculated with a base temperature of 4·5°C) failed to give a significant relationship for the four standard genotypes in Experiments 1, 2 and 6 (incl. Osprey), even when ignoring the crops affected by lodging (Fig. 6). A uniform relationship was not to be expected in Fig. 6 because of large genetic differences in kernels per unit chaff weight and hence in kernels per m² between UQ189/WW33G/Osprey with high kernel numbers and Yecora with low ones (Stapper and Fischer 1990*b*). It is noteworthy that even unlodged crops of Yecora appeared to fall below the relationship determined in Mexico.

Because yield components like kernel number could not be confidently corrected for lodging, further examination of relationships to PTQ will consider only calculated potential yields. Potential yields of all genotypes in Experiments 1, 2 and 6 were related with PTQ for the 30 days prior to anthesis. PTQ was now calculated with a base temperature of 0°C to allow comparison with relationships found by Rawson (1988) shown
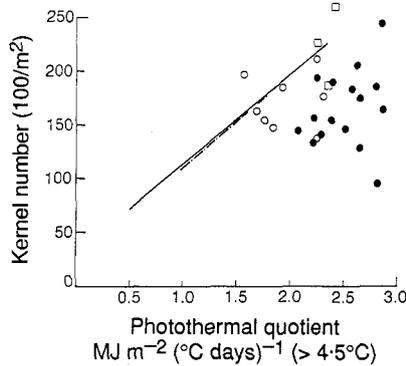
Fig. 6. Kernel number per m² as a function of photothermal quotient over 30 days prior to anthesis for the four standard genotypes in Expts 1 and 2 (○, ●) and three genotypes in Expt 6 (□). Open symbols refer to none or minor lodging, closed symbols to severe lodging. The relationships are for Yecora (–·–·) and other genotypes (——) in Mexico (see text).

Fig. 7. Predicted potential grain yield as a function of photothermal quotient over 30 days prior to anthesis for the four standard genotypes in 1983 (○), 1984 (●) and 1985 (□). The broken lines refer to relationships reported by Rawson (1988) for controlled environment crops (line *A*) and field crops in Mexico (line *B*). *Line C* is the relationship for all genotypes in Expts 1, 2 and 6.

in Fig. 7. Our data (Fig. 7; standard genotypes shown only) fall largely between lines reported by Rawson, which represented regressions for controlled environment studies (Evans 1978; Rawson 1988) and the abovementioned field study in Mexico (Midmore *et al.* 1984). The correlation was significant (Fig. 7 line *C*; $r = 0.47**$, $n = 66$), but the relationship explained only 22% of the variation in yield. There was a large difference in the development stage of the spike at 30 days prior to anthesis. Crops flowering in mid-September started this period at the flag leaf stage while crops flowering in November still had 3.7 leaves to unfold. PTQ calculated for different periods and base temperatures did not improve on the 30-day correlation.

The PTQ values for our study in Figs 6 and 7 are generally higher than those for the Mexican and glasshouse studies, especially with early flowering. Other constraints, such as extreme low or high temperatures encountered in the southern New South Wales environment, may therefore prevent yield (or kernel numbers) to increase despite the extra irradiance available per unit development time.

Effects of Temperature and Irradiance on Yield

Temperature (Fig. 8*a*) and irradiance (Fig. 8*b*) over 500°C days (>3°C) for a maximum of 60 days before anthesis (500°C days/60 days) better explained variation in grain yield than over either a 30 or 60 day period, and the following results refer to this period unless stated otherwise. The 500°C days/60 day period resulted in approximately a 30-day period for late flowering and a 60-day period for early flowering, roughly coinciding with the period between terminal spikelet and anthesis date (Stapper and Fischer 1990*a*). There was a significant negative association between predicted potential yield (Y_p) and average temperature (T) prior to anthesis for the combined data of Experiments 1, 2 and 6:

$$Y_p = 1407 - 51 \cdot 6T \ (g/m^2) \qquad (r = -0 \cdot 68^{**}, \ n = 66). \qquad (2)$$

It follows from equation 2 that an average pre-anthesis temperature of 10°C (anthesis on 16 September: Fig. 8*a*) corresponds with a yield of 900 g/m², with a decrease of 52 g/m² (or 6%) for each 1°C temperature rise. This compares with a 4% reduction in grain yield per 1°C above 15°C (30-day average) for Yecora crops in Mexico (Fischer and Maurer 1976). Reductions in kernels/m² are the likely cause of lower yields when pre-anthesis temperatures are high (Fischer and Maurer 1976; Midmore *et al.* 1982).

Total irradiance over the defined period (Fig. 8*b*) had a positive but non-significant association with yield ($r = 0 \cdot 32$). However, yield differences between the years (Fig. 5) appeared to be associated with differences in cumulative irradiance. Total irradiance over fixed periods of 30 or 60 days (i.e. average irradiance) gave negative, non-significant
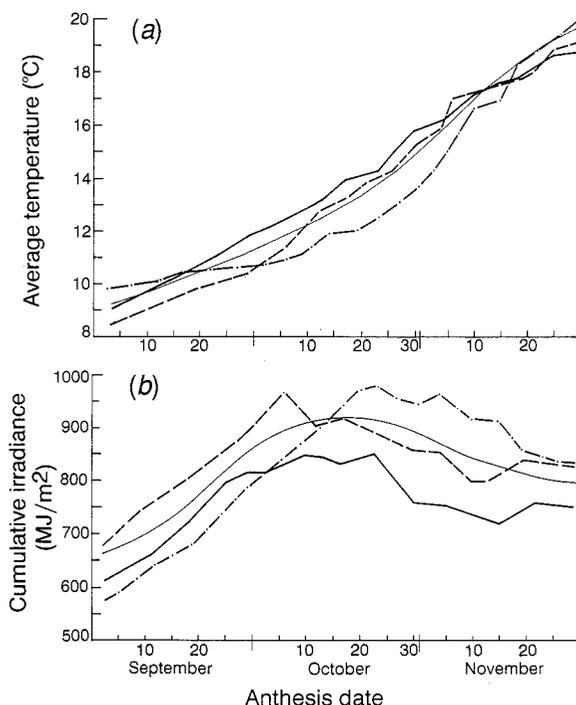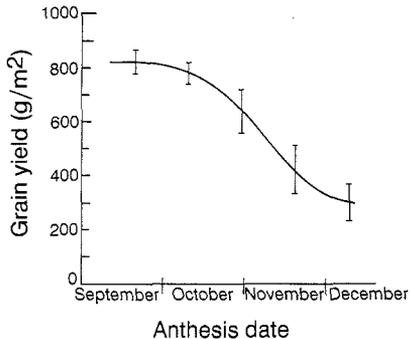

Fig. 8. Average temperature (*a*) and cumulative irradiance (*b*) over 500°C days (maximum of 60 days) prior to anthesis for dates in spring for long-term means (———), 1983 (▬▬▬), 1984 (—··—) and 1985 (— — —) at Griffith, N.S.W.

Fig. 9. Relationship between predicted potential yields (g/m², oven dry) and anthesis date for long-term weather data at Griffith, N.S.W. The relationship is based on a multiple regression equation which includes average temperature and cumulative irradiance over 500°C days (maximum of 60 days) prior to anthesis. Vertical bars are twice the standard deviation.

correlations with potential yield, which resulted from these periods not being related to a common phase of crop (spike) development.

A multiple regression of potential yields with average temperature and total cumulative irradiance (ΣR, MJ/m²) for the 500°C days/60 day period before anthesis gave the following equation:

$$Y_p = 981 - 53.4T + 0.51 \, \Sigma R \text{ (g/m}^2) \quad (r = 0.78**, \, n = 66). \tag{3}$$

The equation explained 61% of the variation in grain yield, compared with 46 and 22% when only considering temperature or PTQ, respectively, over the same period. It follows from equation 3 that a preanthesis temperature increase of 1°C can be compensated by a rise in irradiance of $1.7-3.5$ MJ m^{-2} day^{-1}. This compares with $2.6-3.6$ MJ m^{-2} day^{-1} for a rise of 1°C in post-anthesis temperatures reported by Vos (1981).

Potential yields for alternative anthesis dates were calculated from equation 3 using historical weather data and the average response is shown in Fig. 9. Yields are representative for the present genetic material in absence of lodging. This analysis suggests that predicted yields in an average year are reasonably stable when flowering occurs prior to mid-October. The negative effects of increasing temperatures were balanced by the positive effects of increased irradiance interception by crops flowering in this period (Fig. 8). After mid-October predicted yield decreased by 70 g/m² or 11% per 1-week delay in anthesis as temperatures kept on rising while irradiance interception over the specified period remained constant. Anthesis dates in this period are delayed by $0.3-0.4$ day per day delay in sowing (Stapper and Fischer 1990a), and yield reductions due to delayed sowing can therefore be estimated as 3 to 4% per week. Predicted yields levelled off when anthesis occurred in December. A more detailed analysis of genotype, sowing date and climate interactions is possible with a crop simulation model (Stapper and Harris 1989). Such an analysis is planned after improving a general wheat crop model (Stapper 1984) with the results from the present studies.

Effects of Temperature on Kernel Weight

Fig. 10 presents the kernel weights for the four standard genotypes in Experiments 1, 2, 4 and 6 as a function of average grain-filling temperature. Reductions in kernel weight of 1.8 mg/°C (Fischer 1983; Yecora in Mexico: line A, Fig. 10) and 2.9 mg/°C (Willington and Biscoe: Avalon in England, line B; ref. by Weir *et al.* 1984) have been found for increasing grain-filling temperatures. McDonald *et al.* (1983) reported a curvilinear relationship between kernel weight and grain-filling temperature (line C, Fig. 10) for 15 genotypes grown at various sowing dates. However, because of large genotypic differences in kernel size, kernel weight reductions need to be expressed as a percentage rather than an absolute weight loss per 1°C rise in temperature when evaluating temperature effects across genotypes. Kernel weight reductions were calculated for each genotype as a percentage of
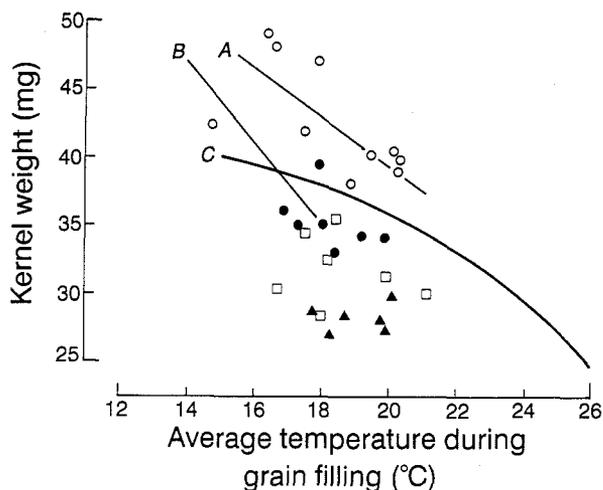
Fig. 10. Kernel weight as a function of average temperature during grain-filling for Yecora (○), Egret (●), WW33G (□) and UQ189 (▲) in Expts 1, 2, 4 and 6. The relationships were reported for Yecora in Mexico (*A*), Avalon in England (*B*) and 15 genotypes in Narrabri, N.S.W. (*C*) (see text).

maximum kernel size from thinned rows in Experiment 1 (i.e. 49, 46, 42 and 38 mg for Yecora, Egret, WW33G and UQ189, respectively: Stapper and Fischer 1990*b*). A general weight reduction of 5% per 1°C temperature rise above 14°C was estimated, when ignoring low kernel weights of severely lodged crops. The 14°C threshold was based on Weir *et al.* (1984) for wheat grown in Britain.

Kernel weight, however, was not directly affected by temperature as kernel weights for low kernel densities (thinned rows) at high temperatures were close to the maximum weight at cooler filling periods (Stapper and Fischer 1990*b*). The estimated response to temperature is therefore only an apparent one and is confounded by changes in kernel densities.

Average long-term temperature during grain-filling increases at a rate of 0·1°C/day from 14·0 to 20·8°C for DC65 between 4 September and 15 November, respectively. Hence, flowering dates with a low frost risk (>22 September; Stapper and Fischer 1990*a*) are likely to have grain-filling temperatures above the threshold associated with reduced kernel weights. Rising grain-filling temperatures during September would suggest a decrease in kernel weights of 3·5%/week. Predicted potential yields, however, were stable in this period (Fig. 9), suggesting that falling kernel weights therefore were balanced by rising kernel numbers, presumably in response to a rise in irradiance levels (Fig. 8*b*). Temperature effects on kernel weights in October also suggest a 3·5%/week decrease, and seems to be the main cause for the calculated 5%/week yield decrease in this period (Fig. 9) as pre-anthesis period total irradiance levels off (Fig. 8*b*). Kernel weight reductions of 2·5%/week were derived for November, which only partly accounts for the 11%/week yield reduction during that month. Lower kernel numbers appear therefore to be the major cause for yield reduction in that period as total irradiance levels drop (Fig. 8*b*).

Optimum Anthesis Dates

Irradiance and average temperature suggest maximum yield with flowering in September (Fig. 9). Frost risk is therefore the factor that determines the start of the

optimum flowering period. Yield losses caused by frost damage for crops flowering in late September were estimated to be up to 20% of potential for some genotypes in the present studies (e.g. S6 Experiment 2 in 1984). Frosts in the area are never severe in this period and crops flowering a couple of days earlier or later were not affected. Flowering should not occur before 22 September as spike emergence has to occur after 10 September. This is when the frost risk is reduced to one night per 5-day period (Stapper and Fischer 1990a). It is safer to use vernalization sensitive (maturity ratings 4, 5) than insensitive (1, 2, 3) genotypes for flowering at this limit as they have greater elasticity, that is, less movement in flowering dates with changes in sowing date (WW33G: 0·28 day/day; Egret: 0·42 day/day; Yecora: 0·58 day/day). Yield reductions for flowering up to as late as mid-October are not large, but later flowering requires more irrigations as the evaporation deficit increases rapidly in spring. It is suggested that the optimum anthesis period therefore covers the last week of September and the first week of October. Frost damage can be minimized by spreading flowering dates, and thereby harvest dates, for various crops on a farm.

Description of an Irrigated Wheat Ideotype

Our results show that, under high-input conditions, lodging is a major yield reducing factor for many genotypes and sowing dates examined in the present studies. Most released varieties appeared susceptible to lodging, reflecting selection under only moderate yielding conditions. Improved varieties should have an increased resistance to lodging. Genotypes with reduced stature and very early maturity seem ideal for achieving high yields efficiently, but considerations of optimum anthesis date and optimum anthesis dry weight will determine the ideotype for a given sowing date. Excessive pre-anthesis dry matter production characterized early (<July) sowing dates and increased lodging risk. The optimum range for dry weight at anthesis was 800–1000 g/m^2 to assure a high harvest index and low lodging risk (Stapper and Fischer 1990b).

For May/June sowings, a medium-early maturing genotype with a vernalization requirement higher than Yecora but lower than Egret will be most suitable, that is, maturity group 2–3 (Table 1; see Fig. 2b, Stapper and Fischer 1990a). Flowering will then occur during the last week of September or the first week of October and dry weight at anthesis will be in the optimum range. For June/July sowings excellent opportunities exist for a very early maturing variety (group 1, Table 1), similar to Yecora for which it was demonstrated that high yields can be combined with high protein concentration (Stapper and Fischer 1990b). Such an early variety is presently not commercially available. Sowing in March and April seems to be incompatible with an aim for high, profitable yields because high dry weights at anthesis are associated with increased lodging risk and unfavourable grain and nitrogen harvest indices. If sowing early, then winter wheats of maturity groups 6 (e.g. Owlet) and 5 (e.g. Osprey, Rosella) are suitable for March/April and April/May sowing dates, respectively. Target grain yield, however, should be restricted to 5–6 t/ha to avoid severe lodging, but these sowings will permit grazing as an additional benefit without necessarily sacrificing yield (M. Stapper, unpublished data).

Grain quality is important to the profitability of irrigated wheat. Soft wheats of biscuit quality are not suitable for high yields as protein concentrations are likely to exceed the threshold of 9·5% (Stapper and Fischer 1990b). Other soft (A.S.W.) and hard wheats can be grown for all sowing dates, with differences in grain protein concentration generally larger between genotypes than between sowing dates. Protein levels increase slowly with delayed flowering (0·4–0·5%/°C: Vos 1981; Stapper and Fischer 1990b) and hard wheats may therefore obtain better quality at later flowering dates.

There is no recommendation for optimum yield components as large genetic differences in, for example, potential numbers of components or potential kernel weight did not result in significant differences in yield due to compensation between components (Stapper and Fischer 1990b). Spike density did not restrict yield, but genotypes with low spike-bearing capacity (restricted tillering or low tiller survival) seemed to perform well under our

conditions, for example, Yecora, Harrier, WW425, and triticales (Stapper and Fischer 1990*b*). A low tiller and spike density allows more light to the crown of the plant which has been reported to reduce lodging (Pinthus 1973).

Meanwhile, lodging in present varieties grown for high yield can be minimized by (i) avoiding very susceptible varieties, and (ii) delaying anthesis with later sowing as this reduces both crop height and dry weight at anthesis (Stapper and Fischer 1990*a*, 1990*b*). The second option increases the risk of not sowing at all in a wet winter and increases the number of irrigations. Other management strategies to minimize lodging are to avoid irrigation when expecting windy conditions and to ensure good surface drainage to keep the period of weak soil strength to a minimum. Low sowing rates or wide row spacings decreased lodging risk but did not improve yields (Stapper and Fischer 1990*b*), and are not recommended for commercial practice because of increased risks of low plant establishment and weeds. Separate studies suggest the possibility of reducing risk without sacrificing yield by delaying nitrogen application until DC31 (R. A. Fischer, unpublished data).

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