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Density and row spacing effects on irrigated short wheats at low latitude

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SUMMARY

During four winter seasons eight spacing and density experiments were made under irrigated high fertility conditions in north-west Mexico (latitude 27°N). Experiments included various *Triticum aestivum* and *T. durum* genotypes of spring habit, short stature derived from Norin 10 genes, and contrasting plant type. Measurements included dry-matter production, photosynthetic area index, and light interception during one experiment, total dry matter at maturity in most others and grain yield and its numerical components in all experiments.

Grain yield and most other crop characters were unaffected by row spacings within the range 10–45 cm interrow width. The optimal seeding density for maximum grain yield was 40–100 kg/ha (80–200 plants/m^2). Yield reductions at lower densities (20, 25 kg/ha) were slight and accompanied by reduced total dry-matter production. Yield reductions at higher densities (160–300 kg/ha) were also slight and were associated with more spikes/m^2 but fewer grains/m^2 and reduced harvest index. It is suggested that lower than normal preanthesis solar radiation or weather conditions leading to lodging can magnify these yield depressions at higher densities.

Measurements showed rapid approach of crops to 95 % light interception, reached even at a density of 50 kg/ha within 50 days of seeding. It is suggested that provided this occurs before the beginning of substantial dry-matter accumulation in the growing spikes (60 days after seeding) there will be no loss of grain yield with reduced seeding density. Results point to a ceiling photosynthetic area index for maximum crop growth rate although there was a tendency for rates to fall at very high indices (> 9). This tendency was associated with very high density, high maximum numbers of shoots, poor survival of shoots to give spikes (< 30 %) and reduced number of grains/m^2. The relatively low optimal densities seen here may be characteristic of genotypes derived from Norin 10.

Genotype × spacing, genotype × density and spacing × density interactions were generally non-significant and always small. There was a tendency for the presence of non-erect leaves or branched spikes to reduce the optimal density, but large differences in tillering capacity had no influence. Differences in lodging susceptibility can however lead to substantial genotype × density interactions.

INTRODUCTION

Extensive agronomic and physiological studies have been conducted at high latitudes (> 30° from the equator) upon the effects of seeding density and row spacing in wheat. From such experiments Holliday (1960) concluded that the optimum seeding density for wheat may vary considerably and is greater the greater the environmental resources (water, nitrogen) or the faster the plants' development (spring wheat versus winter wheat). Using a tall spring wheat grown at high fertility and adequate moisture in England, Willey & Holliday (1971) obtained in a 3-year study maximum grain yield at around 300 plants/m^2 (approximately 150 kg/ha seed) with markedly reduced yield at 90 plants/m^2 and, in 2 years, yield reductions at 600 plants/m^2 or more.

Row spacing effects in cereals were also reviewed

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by Holliday (1963). He concluded that reducing row width below 20 cm tends to increase yield slightly while increases above 20 cm reduce yield; again conclusions were based on studies at high latitudes.

Donald (1963) summarized extensive physiological studies of density effects on crop communities concluding that for most species, including cereals, maximum grain yield is reached at that density at which maximum total dry-matter production is reached. As density increases beyond this point, although dry-matter production remains unchanged, grain yield gradually declines. Puckridge & Donald (1967) confirmed these responses in the detailed study of a tall wheat variety in South Australia; incomplete light interception limited grain yield at low plant densities while excessive light competition, stimulated senescence of lower leaves, tiller death and lodging appeared to be associated with lower yield at very high densities.

Extensive areas of wheat are grown under irrigation at latitudes less than 30° in India, Pakistan, Egypt, Sudan and Mexico. These crops differ in several respects from the situations summarized above:

(i) The environmental resources water, nitrogen and solar radiation are likely to be supplied to the crop in greater quantities.

(ii) Varieties presently grown are only of spring habit and usually of semi-dwarf stature, invariably as the result of the incorporation of Norin 10 dwarfing genes.

There has been considerable agronomic experimentation covering density effects for these conditions in India (Agarwal, Moolani & Tripathi, 1972) and Mexico (CIANO, 1968–9; Vela, 1971; Martinez, 1973). In general these studies suggest that when seeding at the optimal planting date (November in the northern hemisphere) there is no change in yield between 40 and 100 kg/ha of seed, with some tendency for reduced yields at densities above 100 kg/ha, especially if lodging occurs. Variety × density interactions are small. When the seeding date is later than optimal (late December, January) the optimal seeding density may be above 100 kg/ha and 40 kg/ha is clearly sub-optimal. With respect to spacing, Vela (1971) reports in Mexico no change in yield with spacings from 15 to 45 cm, but at 60 cm yield declined. Few of the above studies included the newer dwarf varieties and none considered in detail the physiological basis of the observed yield responses.

The present study was undertaken first to collect more information on the physiological basis of the yield responses to density and spacing of short wheats in the low latitude irrigated environment of northwest Mexico. The second aim was to look at the responses of the newer plant types being developed in the breeding programme of the International Maize and Wheat Improvement Centre (CIMMYT); these included wheats below 90 cm in mature plant height, called dwarf wheats here, wheats of high and low tillering capacity, erect leaf selections and branched spike types. Genotypes of both bread wheat (*Triticum aestivum*) and durum wheat (*Triticum durum*) were studied. In order to uncover possible genotype interactions a wide range of densities and spacings were used.

MATERIALS AND METHODS

Experiments were made during the winter cropping cycles 1970–1, 1971–2, 1972–3 and 1973–4 (henceforth referred to as 1971, 1972, 1973 and 1974 respectively) at the Centro de Investigaciones Agricolas del Noroeste (CIANO), located near Cuidad Obregon, Sonora, Mexico (latitude 27° N, altitude 40 m). The climate, characterized by a short, mild winter and warm to hot spring, with very little rain or cloudiness, is typical of many low latitude situations where irrigated wheat is cultivated during the winter season. Weather conditions during the 4-year study period were close to normal,

Table 1. *Maximum and minimum mean monthly temperature and solar radiation*

	Season				
Month	1970–1	1971–2	1972–3	1973–4	Long* term
	Maximum temperature (°C)				
November	30·0	28·0	26·3	30·2	29·0
December	24·7	23·0	24·7	25·6	24·2
January	23·7	23·8	21·8	23·0	23·2
February	24·0	26·5	24·1	24·8	24·8
March	28·9	29·7	24·8	26·3	27·2
April	30·1	34·0	29·4	32·7	31·4
	Minimum temperature (°C)				
November	10·4	10·8	10·6	9·8	11·6
December	8·2	7·9	9·4	6·4	8·6
January	3·7	6·6	5·9	6·6	6·8
February	5·1	6·4	8·9	4·5	6·8
March	7·1	10·1	7·3	8·8	8·2
April	9·4	9·2	8·0	9·1	10·5
	Solar radiation (Langley's/day)				
November	346	346	353	355	350
December	278	284	280	317	290
January	331	297	306	313	312
February	409	405	359	418	398
March	535	523	520	488	517
April	602	605	615	589	603

* 1960–74 except solar radiation which refers to 1970–4.

Table 2. *Characteristics of row spacing (cm) and seeding density (kg/ha) studies**

Expt	Year	Treatment	Subtreatment	Subsubtreatment
1	1971	50, 100, 200, 300 kg/ha	10, 20, 30, 40 cm	—
2	1972	4 bread wheats	15, 30, 45 cm	40, 100, 250 kg/ha
3	1972	4 durum wheats	15, 30, 45 cm	40, 100, 250 kg/ha
4	1973	2 bread + 2 durum wheats	15, 30 45 cm	40, 100, 250 kg/ha
5	1973	15 cm × 250 kg/ha 30 cm × 100 kg/ha 45 cm × 40 kg/ha	8 bread wheats	—
6	1973	As for 5	8 durum wheats	—
7†	1973	25, 75, 225 kg/ha	5 bread + 5 durum wheats	—
8†	1974	5 bread + 5 durum wheats	20, 40, 80, 160, 240 kg/ha	—

* Rows always oriented north south.
† Row spacing constant at 20 cm.

the only significant departures being a week of frosts in early January 1971, and heavy rain and considerable cloudiness in February 1973 (Table 1).

All experiments were of split-plot design with three or four replications (Table 2). Genotypes consisted of advanced lines and current varieties of bread wheat or durum wheat; these were all dwarf or semi-dwarf in statute, and of acceptable maturity. Experiment 1 contained only one genotype, the dwarf bread variety Yecora 70; this variety, one of the highest yielding presently grown in northwest Mexico, was present in all other experiments containing bread wheats. It is heavy tillering with a non-erect leaf habit. The semi-dwarf variety Cocorit 71 similarly served as a control in the experiments with durum wheats; it is also non-erect.

Experiments received optimal agronomic management. Thus seeding dates were between 16 and 27 November with the exception of Expt 7, which was seeded on 11 December. The soil type was a clay, low in organic matter, but of moderate fertility: 200 kg N/ha (as urea) and 80 kg P_2O_5/ha (as triple superphosphate) was applied at seeding time. Seeding was done into dry soil and irrigation by flooding followed. Subsequent irrigations every 15–35 days were sufficiently frequent to avoid any visible signs of plant water stress. Weeds, controlled by hand, and diseases were never significant.

The experimental unit was usually about 2×2 m^2; from this a quadrat of 1·0–1·5 m^2, adequately bordered on all sides, was taken at maturity. Grain yield, number of spikes/m^2, number of spikelets/spike and kernel weight were always determined. From these, number of grains/spikelet, number of spikelets/m^2 and number of grains/m^2 were calculated. In most experiments total dry weight and harvest index were also determined. All weights are oven-dry weights (70 °C) unless otherwise mentioned.

In all experiments plant counts were taken 3–4 weeks after seeding. Time to 50 % spike emergence and 50 % spikes without green colour (maturity) were noted. Plant heights and the incidence of lodging were always recorded. In Expts 5–8 there was considerable variation in leaf angle amongst genotypes; leaf angle was therefore scored visually every 2 weeks or so.

Experiment 1, in addition to the above data collection, involved the study of crop growth (dry-matter accumulation), photosynthetic area index, tillering, and light interception. Growth, area and tillering were measured on 0·35 m^2 quadrat cuts taken at 46 and 92 days after seeding. Photosynthetic area comprised the sum of the green lamina area, plus half the green stem-sheath surface area and half the green spike surface area. Spike surface is defined as spike length × breadth across a single central spikelet × 4.

Light interception was measured every 10 days or so in Expt 1 using a modification of the method of Friend (1961). Sensors containing light sensitive ozalid paper positioned below a $20 \times 0{\cdot}7$ cm^2 rectangular window, were placed under the crop in the field with the window facing upwards and perpendicular to the row direction. Sensors outside the crop acted as controls. The method has the advantage of integrating the radiation reaching the soil surface over appropriate intervals of time (sampling all sun angles) and space (the row width). It is quite accurate for determining radiation interception by the crop at high levels of interception (> 80 %). However, as Kanemasu, Feltner & Vesecky (1971) point out, this method, due to the spectral response of ozalid paper, only senses radiation in a narrow spectral band, 350–450 nm. Interception of such radiation in the canopy may differ from interception of photosynthetically active radiation (400–700 nm).

RESULTS

Number of plants and development

Experiments were seeded in dry soil and then irrigated; slow drying of the surface of this heavy cracking soil due to excessive flooding or subsequent rain has been observed to reduce seeding emergence. However, this did not occur in any experiment and the number of plants was consistently related to seeding density regardless of experiment (Fig. 1). The Yecora 70 data are typical of the bread wheats, which had kernel weights of around 40 mg, and that for Cocorit (mean kernel weight around 46 mg) typical of the durum wheats. The small differences in number of plants between genotypes at any given density were negligible relative to the differences due to density levels.

Increased density hastened plant development. This was consistent over experiments and genotypes. A doubling of density reduced the interval from seeding to 50 % spike emergence by about 3 days and reduced the interval from seeding to 50 % spike maturity by about 2 days. Row-spacing treatments had no consistent influence and development differences between extremes of spacing were never greater than 2 or 3 days. The approximate range from seeding to spike emergence for the genotypes used was 70–100 days; for maturity the corresponding figures were 120–135 days.

Experiment 1

Crop growth

Total dry weight (g/m^2) of the crop (above ground) was measured at 15, 46 and 92 days after seeding and at maturity (Table 3). Forty-six days corresponded to the date of maximum number of shoots (approximate stage of terminal spikelet on the main shoot apex), while the 92-day sampling came at or up to 7 days after 50 % anthesis. Increased density gave increases in total dry weight at all dates except at maturity. At 15 days, crop dry weight was proportional to density; at later dates relative differences became small. Reduced spacing gave small but significant increases in total dry weight at 15 and 46 days. There was no significant spacing × density interaction.

Treatment effects on photosynthetic area index (PAI) follow effects on total dry weight with small modifications early on due to density effects on the

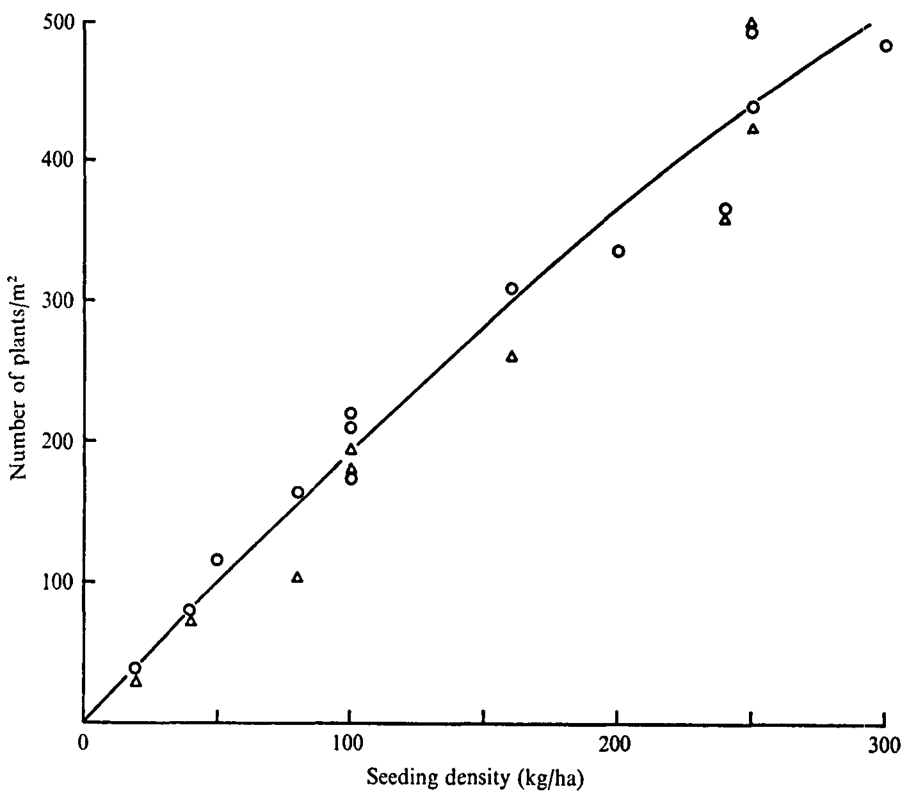

Fig. 1. Number of plants as a function of seeding density; all experiments, genotypes Yecora 70 (circles) and Cocorit 71 (triangles).

Table 3. *Effects of density and row spacing on crop growth, grain yield and associated characters: Expt* 1

Treatment	Total dry weight (g/m²) 15 days	46 days	92 days	maturity	Grain dry wt. (g/m²)	No. of shoots/m² 46 days	No. of spikes/m²	No. of spikelets/spike	No. of grains/spikelet	No. of grains (100/m²)	Kernel wt. (mg)
Density (mean of spacings)											
50 kg/ha	5·4	200	944	1624	706	912	403	19·6	2·17	171	41·2
100 kg/ha	10·0	244	1012	1627	708	1088	440	19·1	2·03	172	41·5
200 kg/ha	15·5	287	1013	1669	704	1250	465	17·8	2·04	170	41·8
300 kg/ha	24·3	318	1012	1647	692	1446	458	17·1	2·08	163	42·4
S.E.	0·6	9	32	30	9	35	8	0·2	—	3	—
Spacing (mean of density)											
10 cm	15·5	277	958	1620	687	1354	434	18·5	2·06	164	41·8
20 cm	14·4	274	1073	1654	706	1286	444	18·6	2·07	171	41·6
30 cm	13·0	262	979	1619	695	1075	437	18·3	2·11	167	41·6
40 cm	12·4	235	971	1674	723	982	451	18·3	2·09	174	41·9
S.E.	0·6	5	25	35	13	26	11	0·2	—	3	—

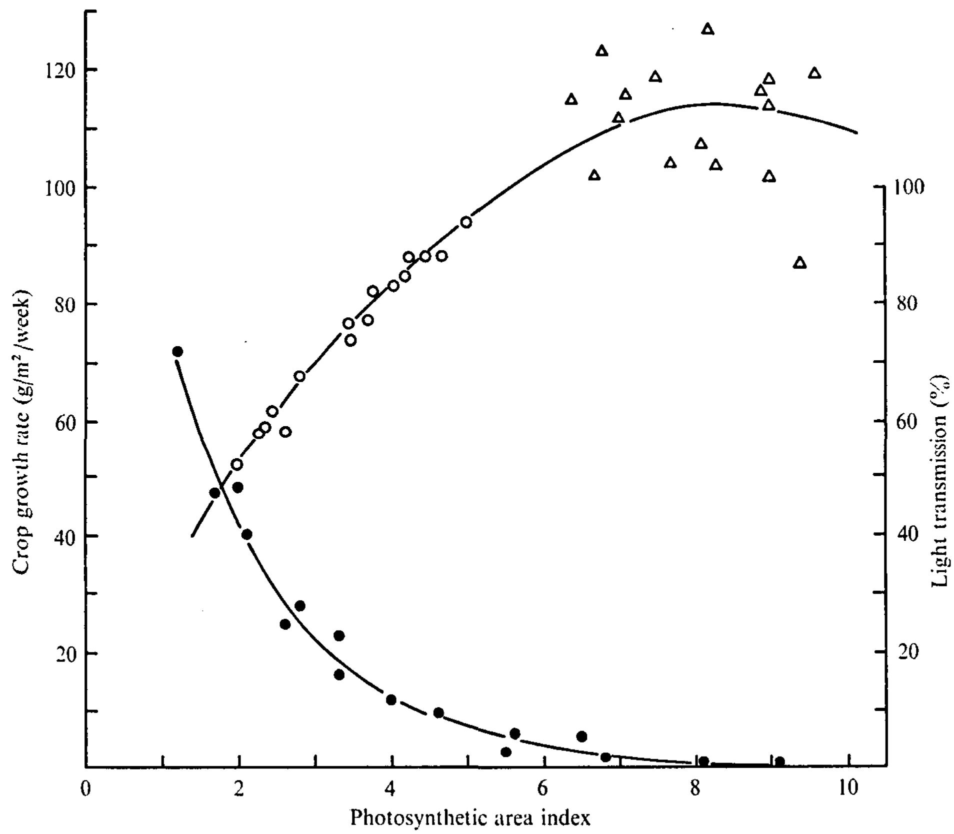

Fig. 2. Relationship of crop growth rate (open symbols) and light transmission (closed symbols) to photosynthetic area index (PAI); Expt 1. Crop growth rate of all treatments for the periods 15–46 days (circles) and 46–92 days (triangles) from seeding. Growth rate in the first period is corrected for the difference in solar radiation intensity by multiplying by 1·32 or the ratio of the mean radiation intensity of the period 46–92 days (373 ly/day) to that of the period 15–46 days (283 ly/day). Light transmission measurements made on days 22, 26, 35 and 54 and averaged for the four spacing treatments on each occasion.

photosynthetic area ratio (photosynthetic area per unit dry weight). At 46 days this ratio was increased by increased density (+20 % at 300 kg/ha compared with 50 kg/ha). Crops were generally very leafy with maximum PAI values close to 10.

Early differences in crop growth rate are related to differences in light interception. The relationship of mean crop growth rate (g/m²/week, Y) over the period 15–46 days from seeding to mean percentage of light intercepted in the same period (X) was $Y = 0{\cdot}84X - 7$ ($r = 0{\cdot}91$; $P < 0{\cdot}01$) over all density spacing combinations. Light interception was curvilinearly related to PAI, a relationship unaffected by density and only slightly by spacing. Row spacing at 40 cm caused slightly less interception per unit PAI, probably because the marked clumping of foliage in the wider rows caused greater mutual shading.

Figure 2 shows that 95 % light interception was reached at a PAI of around 6. The first treatment to reach 95 % of full light interception (density 300 kg/ha, spacing 10 cm) did so by about 35 days from seeding, compared with 55 days for the last to do so (density 50 kg/ha, spacing 40 cm). After this date differences in light interception between treatments were very small and mean crop growth rate from 46 days to maturity was similar for all treatments (averaging 117 g/m²/week). Similarities in crop growth rate from 46 days onwards taken along with the small delays in maturity with decreased density or wider row spacing meant that total dry weight at maturity showed no significant effects of treatment.

The crop growth data for the 46- to 92-day period is combined with that for the 15- to 46-day period to show the relationship between crop growth rate and PAI (Fig. 2). The data generally suggest a critical PAI (about 7) for maximum growth rate; this corresponds fairly closely to the point of 95 % light interception and as such agrees with Puckridge & Donald's (1967) observations for their wheat crop until the early jointing stage (corresponding to about day 46 here). Subsequent to this stage they showed markedly decreased crop growth rates with leaf area indices above about 4·5. In contrast, here there is only a weak tendency for depressed growth rates after jointing (46–92 days) with the most leafy crops.

Grain yield and components

Although there were statistically significant effects of spacing on early tillering and of density on most numerical components of yield as well as tillering, there was no significant effect of treatment on grain yield (Table 3). Also there were no significant spacing × density interactions. Grain yields were high, ranging from 7·65 to 8·36 t/ha at 12 % moisture, and were measured with good precision (the coefficient of variation was only 4·9 %).

The large early differences due to density and the smaller ones due to spacing in terms of number of shoots/m² had entirely disappeared by anthesis (see number of grains/m² in Table 3). This was due to large compensatory changes in the percentage of shoots surviving to give spikes and smaller ones in number of spikelets/spike and number of grains/spikelet. Looking at the 16 spacing × density combinations some significant trends are evident in the data. Number of shoots/m² at 46 days ranged from 782 to 1738; percentage shoot survival was inversely related to number of shoots ($r = -0{\cdot}96$; $P < 0{\cdot}01$) and fell from 51 % (40 cm, 50 kg/ha) to as low as 25 % (10 cm, 300 kg/ha). Correlated with shoot survival over the 16 treatments was number of grains/m² ($r = 0{\cdot}62$; $P < 0{\cdot}05$) and grain yield ($r = 0{\cdot}66$; $P < 0{\cdot}01$). Grain yield was correlated with number of grains/m² ($r = 0{\cdot}91$; $P < 0{\cdot}01$) and inversely with number of shoots/m² at 46 days ($r = 0{\cdot}56$; $P < 0{\cdot}05$). Thus the good early start in terms of crop growth or potential yield components provided by high seeding density and narrow row spacing actually tended to depress the number of grains/m² and grain yield. These effects are in the same direction, although less marked, as those observed by Puckridge & Donald (1967). Since there was no lodging here, they can be attributed to excessive competition and overcompensation amongst early numerical components of yield. The fact that such crops reached anthesis sooner and therefore had less time to form their early yield components does not explain this effect since they also reached 95 % light interception sooner; estimated crop dry weights at anthesis were very similar for all treatments.

Experiments 2–8

All experiments except Expt 1 comprised several genotypes. Experimental errors for grain yield were low (coefficients of variation ranged from 5 to 10 % except for Expts 6 (15 %) and 7 (15 %)). Genotype interactions with row spacing or density were, with three minor exceptions, not significant. Also there were no significant spacing × density interactions. Thus Tables 4 and 5 summarize separately spacing

Table 4. *Effect of row spacing on grain yield (g/m²): mean of all genotypes and densities*

Row spacing (cm)	Experiment no. 2	3	4	Mean
15	520	562	523	535
30	523	585	538	549
45	506	549	535	530
S.E.	6	7	7	

and density effects, using the mean values for all genotypes in each experiment.

Spacing results shown in Table 4 generally agree with the data shown for Yecora in Expt 1. Effects of row spacing on grain yield were usually not significant and always very small. Similarly effects on yield components (not presented here) were small. Apparently rows can be spaced as wide as 45 cm apart without yield being depressed. However Vela (1971) and other unpublished data suggest that 60 cm row spacing does depress yield significantly under the conditions tested here.

In Table 5 the effects of density follow, with the exception of Expts 4–6, those observed in Expt 1. Thus grain yield was unaltered by density changes within the range 40–100 kg/ha with a slight tendency for reduced yield both below 40 and above 100 kg/ha. Maximum total dry weight was reached at a density of about 100 kg/ha but even 20 or 25 kg seed/ha produced within 10% of maximum dry weight. The numerical components of yield showed compensation in the case of low seeding densities involving in particular more spikes/plant. Number of spikelets/spike and number of grains/spikelet also increases slightly such that although number of spikes/m^2 was always less with low density, number of grains/m^2 was usually unaffected. As density effects on kernel weight were small, grain yield always followed number of grains/m^2.

Experiments 4–6, all planted around 19 November 1972, showed highly significant and substantial depressions in grain yield with density increases

Table 5. *Effect of seeding density on grain yield and yield components: mean of all genotypes and spacings*

Experiment	Density (kg/ha)	Total dry wt. (g/m²)	Grain dry wt. (g/m²)	No. of spikes/ m²	No. of spikelets/ spike	No. of grains/ spikelet	No. of grains (100/m²)	Kernel wt. (mg)
2	40	1202	510	327	20·5	2·30	152	33·7
	100	1264	526	356	19·5	2·23	153	34·7
	250	1295	517	399	18·0	2·08	147	35·4
S.E.		12	4	4	1·0	0·02	2	0·2
3	40	1330	564	283	19·9	2·34	132	43·4
	100	1368	571	314	18·9	2·20	129	44·8
	250	1412	560	359	17·8	1·95	128	45·0
S.E.		10	4	4	0·1	0·04	2	0·2
4	40	—	589	407	20·0	1·84	146	36·3
	100	—	544	418	18·8	1·84	142	35·6
	250	—	462	451	16·2	1·76	126	33·8
S.E.			7	5	0·1	0·03	2	0·3
5*	40	—	504	398	20·0	1·80	140	51·3
	100	—	466	424	18·8	1·69	132	48·9
	250	—	404	511	17·3	1·44	121	47·1
S.E.			6	11	0·2	0·03	2	0·4
6*	40	—	484	288	21·9	1·55	96	51·3
	100	—	425	310	20·8	1·43	90	48·9
	250	—	386	362	19·9	1·17	84	47·0
S.E.			13	8	0·1	0·06	2	0·7
7	25	1243	516	287	19·9	2·34	126	41·9
	75	1345	545	353	18·0	2·19	133	41·7
	225	1358	499	453	15·0	1·91	126	40·2
S.E.		25	14	5	1·3	0·07	3	0·3
8	20	1502	639	324	23·3	2·18	155	41·9
	40	1546	666	345	23·1	2·18	162	42·0
	80	1576	661	380	22·9	2·01	163	41·5
	160	1561	647	422	20·5	1·90	158	41·7
	240	1534	628	442	20·2	1·86	154	41·6
S.E.		15	7	6	0·3	0·04	2	0·4

* Density effect may be confounded with row spacing effect (see Table 2); however, the latter is quite small in other experiments (see Table 4).

above 40 kg/ha. Most of the 18 genotypes in these three experiments lodged heavily on 21 February following heavy rain and wind. Lodging was greater at higher densities. However several facts suggest that lodging only partly explained the strong negative yield response to density:

(i) Lodging came after 50 % anthesis for most genotypes, up to 10 days after for some, yet their yield depression was related more to fewer grains/m² than to reduced kernel weight. If such lodging had been the key factor, unpublished data for artificially lodged crops suggest that kernel weight should have suffered most.

(ii) Several genotypes with reduced or zero lodging also show depressed yield.

It is suggested that the unusual response to density in 1973 was due in part to the relatively poor radiation regime in the first 3 weeks of February 1973 (see Table 1). In this period most crops passed through or were terminating a pre-anthesis stage of development (that of spike growth) which shading experiments in 1973 and other years have shown is most sensitive to reduced radiation receipts by the crop (Fischer, 1975). Sensitivity was especially great in 1973 presumably due to less solar radiation, including two periods of heavy cloudiness, in February. It is feasible that for this same reason the effect within the higher density crops of increased competition depressing tiller survival and number of grains/spikelet, and hence number of grains/m², was also greater in 1973. Experiment 7, being planted 22 days later, would have largely escaped low radiation during the critical pre-anthesis period, hence explaining its reduced yield depression with higher seeding density. Also the only genotype showing no yield depression with increased density in the experiments planted earlier was very late in reaching anthesis.

Plant type and response to density and spacing

The three significant genotype interactions mentioned earlier were genotype × density interactions in Expts 2–4. The interaction in the first two cases involved such small yield differences that they can be ignored. In Expt 4, however, the two bread wheat entries showed a yield reduction of 154 g/m² as density increased from 40 to 250 kg/ha whereas for the two durum entries the reduction was only 100 g/m². There is no obvious explanation of this difference: the effect of density on lodging was similar in both cases.

Leaf angle

All of the experiments, except Expts 1 and 7, involved genotypes of contrasting leaf angle. Although the 1972 and 1973 results suggest no influence of leaf angle upon density or row spacing responses, the best test of this question is provided by Expt 8 in 1974.

Excluding one genotype which lodged, the other nine of Expt 8 can be divided into five erect and four non-erect types. There were very obvious differences in leaf angle between the groups: the average of leaf angle scores at six dates up to anthesis was 52° (to the horizontal) for the erect group and 32° for the non-erect one. The canopies could clearly be called erectophile and planophile respectively. Despite this contrast, the grain yield response to density (Fig. 3*a*) was not very different for each group, although the tendency towards a greater optimal density with erect types was in the expected direction. The response of grain yield to density closely paralleled that of number of grains/m² and of total dry-matter production.

No effect of leaf angle on responses to row spacing

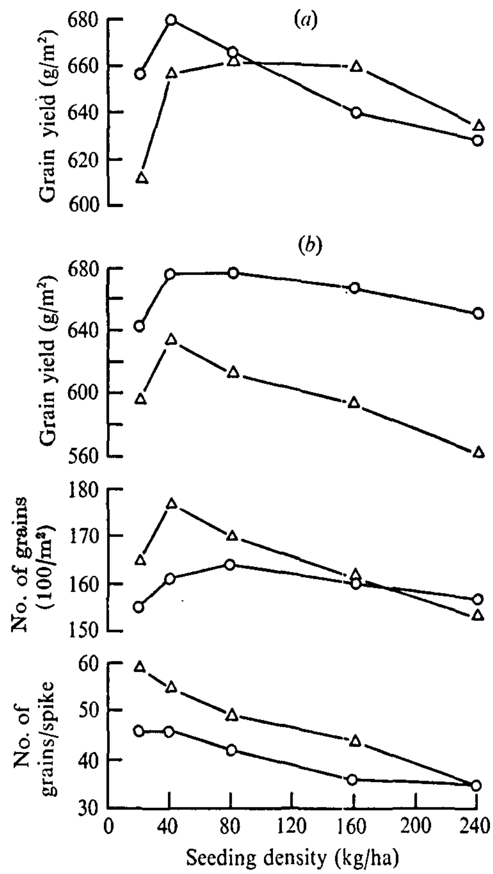

Fig. 3. (*a*) Mean grain yield response to density of erect (△, $n = 5$), and non-erect (○, $n = 4$) genotypes; Expt 8. (*b*) Response to density of mean grain yield, number of grains/m² and number of grains/spike of normal (○, $n = 7$) and branched-spike (△, $n = 2$) genotypes; Expt 8.

were evident in the experiments of 1972 and 1973. However because leaf angle differences were not marked in 1972 and because 1973 results were markedly influenced by the unusual seasonal conditions, the experiments here do not constitute a good test of this important question.

Branched spikes

A bread wheat and a durum genotype both with branched spikes and semi-dwarf stature were included in each of Expts 7 and 8 in awareness of the fact that this character, very striking under spaced-plant conditions, is rather sensitive to interplant competition. The branched spike character in both cases appears to be genetically similar to that found in *Triticum turgidum*. The results of Expt 8 (Fig. 3*b*) show that grain yield in the branched-spike genotypes tended to be more depressed by high density than in the other genotypes, suggesting a lower optimal density for the former. This response parallels the response in number of grains/spike in the branched types (Fig. 3*b*). Under spaced-plant conditions the branched spikes contained 66 % more grains than the normal spikes. The lower yield of the branched types is obviously related to their reduced kernel weight. The results of Expt 7 confirm these observations.

Tillering capacity

Marked differences in tillering capacity were present in the genotypes of Expts 2, 3 and 7. For example the genotypes of Expt 2, Sonora 64 and Siete Cerros 66 produced a maximum number of shoots of approximately 800/m² while Yecora 70 and Cajeme 71 under similar conditions reached 1100/m² or more. Nevertheless their grain yield responses to seeding density and to spacing were not different. Similar contrasts and conclusions can be drawn from Expts 3 and 7.

Lodging

A potential source of significant genotype × density interactions in grain yield is seen in Expt 8 the only experiment, apart from Expts 4–6, where lodging occurred. Here Cocorit 71 showed a steady increase in lodging score (percentage plot lodged × angle to vertical of lodging divided by 90) with increased density; at 20 kg/ha the score was 11, at 240 kg/ha it was 78. The grain yield of Cocorit 71 decreased progressively, a total of 102 g/m² between these extremes; the mean yield of the other nine genotypes, for which there was no significant lodging, was the same at 20 as at 240 kg/ha.

DISCUSSION

Grain yields over all experiments averaged 547 g/m² (6·22 t/ha at 12 % moisture); the best adapted genotypes Yecora 70 and Cocorit 71 approached yields of 8·0 t/ha on several occasions. These are high but not unusual yields for spring wheats in northwest Mexico and reflect the high level of environmental inputs, light, water and nutrients. In the absence of differential lodging, responses to spacing and density were basically the same for all genotypes.

The yield responses to density and spacing agree with those reported earlier for similar low latitude conditions. Optimal densities were from 40 to 100 kg/ha (80–200 plants/m²) although yield, except in 1973, changed no more than 5 % over the whole range of densities tested (see Fig. 4). Optimal densities appear to be somewhat less than those reported for spring wheats at higher latitudes despite the reduced environmental resources in the latter situation (Holliday, 1960). Similarly optimal row spacings (15–40 cm) may be greater. However, it seems that the difference in response is less a latitudinal effect than one due to the genotypes being tested at high latitudes, which were until recently, entirely wheats not derived from Norin 10. Thorne & Blacklock (1971) reported for two semi-dwarf spring wheats, derived from Norin 10, no

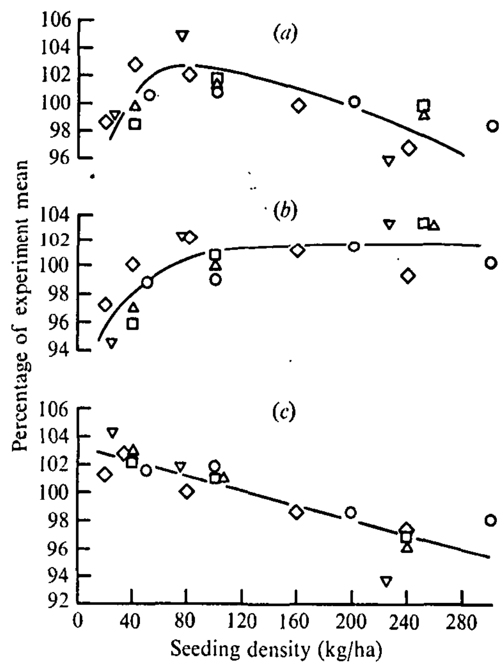

Fig. 4. Response of (*a*) grain dry weight (g/m²); (*b*) total dry weight (g/m²) and (*c*) harvest index to seeding density; Expts 1 (○), 2 (□), 3 (△), 7 (▽) and 8 (◇). Points are the means of all genotypes at each density expressed as a percentage of the experiment mean.

increase in grain yield in England as the density increased from 100 to 200 plants/m^2.

The ability of the genotypes to produce maximum yield from relatively low densities (as low as 40 kg/ha) may depend on the high level of fertility used and particularly on the relatively high tillering capacity of Norin 10 wheats in general (Reitz & Salmon, 1968). Shading experiments (Fischer, 1975) show grain yield in Yecora 70 to be rather insensitive to reduction in early crop growth caused by shading up to 55 days after seeding. It is tempting to suggest that as long as full light interception and maximum crop growth rate is reached by this date (as it was even at 50 kg/ha in Expt 1) maximum yield will be achieved. This date corresponds in Yecora 70 to about 10 days after terminal spikelet formation on the main shoot, and to the approximate point at which spike dry matter accumulation begins. This would suggest the possibility of maximum grain yield being reached at densities somewhat less than those giving maximum dry-matter production, where the lost total dry matter represents unnecessary early growth (cf. Donald 1963). Figure 4 summarizes grain yield, total dry matter and harvest index responses to density in experiments for which these were measured. Maximum grain yield was reached ahead of maximum total dry-matter production and this is the result of a small but clear-cut decline in harvest index as density increased.

A further factor often overlooked which also helps low densities to reach maximum grain yields is the small delay in date of 50 % anthesis. This occurs presumably because more of the emerging spikes arise from later, higher order tillers.

There was a tendency for depressed grain yields, harvest indices and number of grains/m^2 at high densities in most experiments (Fig. 4). These declines were never as marked as reported by Puckridge & Donald (1967) or Willey & Holliday (1971) but these workers studied higher densities (600–1200/m^2) and in the former case lodging was undoubtedly also a factor. In addition the higher solar radiation in our study may have reduced the deleterious effects of strong interplant competition and senescence of lower leaves on the formation of grain yield components (represented by number of grains/m^2). Experiment 1 suggests that with Yecora 70 in a normal year 500 plants/m^2, leading to about 1500 shoots/m^2 at 46 days and less than 30 % shoot survival, may represent a threshold above which there is excessive competition. The fact that above this level of early growth, pre-anthesis crop growth rate tended to decrease (Fig. 2) agrees with the observations of Puckridge & Donald (1967) at high densities. Finally Fig. 3 provides some evidence that the erect leaf character, which one would expect to lessen intershoot light competition, does improve slightly the tolerance to high densities.

These results have several practical implications. First, in the comparison of new genotypes, including ones with differing leaf angles or degrees of spike branching, there is no need for undue concern about possible genotype × density interactions; genotypes can be safely compared within the range 100–200 plants/m^2. Results also suggest that at present commercial seeding densities (100 kg/ha) yield in varieties such as Yecora 70 is limited neither by inadequate nor by excessive tillering capacity; certainly further selection pressures for increased tillering would seem unnecessary. Finally it appears that commercial seeding rates could be reduced by at least 30 % without risk provided the seeding date was optimal, and good seed-bed preparation, high seed quality and weed control were maintained. In particular this would permit the planting of limited supplies of new varieties on larger areas and may also reduce the risk of yield loss due to lodging and other deleterious effects of excessive density such as were seen in 1973.

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