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Effects of wheat seed rate and fertiliser nitrogen application practices on populations, grain yield components and grain yields of wheat (*Triticum aestivum*)

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Abstract Wheat (*Triticum aestivum*) plant and crop responses to seeding rates and fertiliser nitrogen (N) application practices were measured in 19 field experiments undertaken in three successive cropping years. Increasing the number of wheat seeds sown produced more dense wheat populations, reduced both plant grain yield components and plant grain yield, boosted some crop grain yield components but generally failed to improve crop grain yield. Mostly, wheat population was not significantly affected by fertiliser N which enhanced all plant grain yield components (except mean grain weight), plant grain yield, crop grain yield components, and crop grain yield. The high rate of fertiliser N (either 120 or 140 kg N ha^{-1}) had greater effects (including reduction of mean grain weight) than the low rate (either 60 or 70 kg N ha^{-1}). However, the additional positive effects caused by the extra fertiliser N supplied in the high rate were much smaller than those produced by the initial increment. Fertiliser N effects on wheat crop grain yield did not vary significantly with wheat population. Variation of either fertiliser N application time or fertiliser N application mode had little effect on wheat crop grain yield. The negative responses by plant grain yield components and plant grain yield to increases in wheat seed rate and wheat population, and by mean grain weight to applied fertiliser N were the result of self-thinning. It was concluded a low rate of wheat seed (165 seeds m^{-2}) and a single application of a moderate rate of fertiliser N (not exceeding 90–100 kg N ha^{-1}) are sufficient for the successful cultivation of autumn-sown wheat in Canterbury, New Zealand.

Keywords wheat; *Triticum aestivum*; wheat seed rate; fertiliser nitrogen; fertiliser nitrogen application rate; fertiliser nitrogen application time; fertiliser nitrogen application mode; wheat population; plant grain yield components; plant grain yield; crop grain yield components; crop grain yield; self-thinning

INTRODUCTION

The promotion of novel management systems for the cultivation of wheat (*Triticum aestivum* L.) in Canterbury, New Zealand (Batey 1980; McCloy 1980; Macmillan 1980) prompted questions concerning the prudence of recommendations that a high rate of wheat seed (300 seeds m^{-2}) be sown, that a dense wheat crop (250 plants m^{-2}) be established and treated with a high rate of fertiliser nitrogen (N) (200 kg N ha^{-1}) split among two or three part-applications made at different stages of wheat development. In the absence of adequate local field testing of the proposed management systems, three series of field experiments were undertaken to establish the effects of wheat seed rate and fertiliser N application practices on wheat population, plant grain yield components, plant grain yield, crop grain yield components, and crop grain yield.

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MATERIALS AND METHODS

Three series of field experiments, namely series A (experiments 1–6), series B (experiments 7–12), and series C (experiments 13–19), were undertaken in the wheat cropping years 1981–82, 1982–83, and 1983–84 by R. C. Stephen (series A and B) and E. G. Drewitt (series C) (Table 1). Two field experiments of each experimental series were conducted in each wheat cropping year, together with one additional series C experiment in 1982–83. The field experiments were sited on arable soils commonly used for commercial wheat cultivation in central districts of Canterbury, New Zealand.

Fifteen experimental wheat crops were sown in late autumn (May). Because of delays to the cultivation of their sites, experiments 11, 12, 16, and 19 were drilled later, in mid winter (late June/July). At each site, machine-dressed fungicide-treated seed of the wheat cultivar 'Rongotea' (McEwan & Vizer 1979), having a germination capacity of not less than 98%, was drilled with 250 kg ha^{-1} superphosphate (N:P:K:S, 0:9:0:11) into conventionally cultivated seed beds in 10-row plots, each 1.5 m wide and either 30 m long (series A and series B) or 15 m long (series C).

Ten crops were solely rain-fed. The crops of experiments 1, 11, and all series C experiments (13–19) were irrigated at least twice in the late spring/early summer months (October–December).

Each crop was treated as required with applications of herbicide, insecticide, and fungicide. In retrospect, a pre-drilling application of herbicide to control mixed populations of wild oats (*Avena fatua* L. and *Avena persica* Steud.) would have been advantageous for experiments 1, 14, 16, and 18.

The experimental treatments, which included wheat seed rates and fertiliser N application rates, application times, and application modes, differed between each series of experiments. Details of experimental treatments used in each series of experiments are given in Table 1.

Before seeding, the numbers of wheat seeds required to achieve the planned wheat populations were determined by adjusting nominal numbers to compensate for variation in wheat seed germination capacity and an anticipated field establishment of wheat plants (Table 1).

Fertiliser N was broadcast onto appropriate plots in series A and series B experiments as urea (N:P:K:S, 46:0:0:0) and in series C experiments as ammonium sulphate (N:P:K:S, 21:0:0:24). Details of the total quantities or application rates of fertiliser N (kg N ha^{-1}) tested in each series of experiments are given in Table 1.

Table 1 Details of experimental treatments applied to field experiments included in series A, B, and C experiments.

	Series A (experiments 1–6)	Series B (experiments 7 –12)	Series C (experiments 13–19)
Planned wheat populations (plants m^{-2})	75, 150, 225, 300, and 450	150 and 300	175 and 275
Anticipated wheat plant establishment (%)	90	90	80
Wheat sowing rates (seeds m^{-2})	83, 165*, 248, 330, and 495	165* and 330	220* and 339
Fertiliser nitrogen application rates (kg N ha^{-1})	0, 70, and 140	0, 70, and 140	0, 60, and 120
Fertiliser nitrogen application times (wheat growth stages)	Early tillering (GS 22–23) Early stem elongation (GS 32–33)	Early establishment (GS 11–12) Early tillering (GS 22–23) Early stem elongation (GS 32–33)	Drilling (GS 00) Early tillering (GS 22–23) Early stem elongation (GS 32–33)
Fertiliser nitrogen application modes	Single application Divided application (split between 2 times)	Single application Divided application (split between 2 and 3 times)	Single application Divided application (split between 2 and 3 times)

*Base rate of wheat seed.

Details of the fertiliser N application times or specific stages of wheat growth (as defined by Zadoks et al. (1974) and Tottman et al. (1979)) at which fertiliser N was applied are given in Table 1. Most applications of fertiliser N were made after the wheat plants had established. However in series C experiments, the earliest or "drilling" applications (GS 00) were top-dressed onto the surface of seedbed 1 or 2 days after the wheat seed had been sown but before wheat plants had emerged.

Two fertiliser N application modes, single and divided, were compared in each field experiment. For the divided or split application mode the total quantity of each rate of fertiliser N was divided equally between two and three part-applications made at different application times.

Split-split-plot experimental designs were used. In each field experiment wheat seed rate treatments were factorially combined with fertiliser N application rate treatments and the combinations allocated randomly to main plots in twice replicated blocks. In series A experiments, each main plot consisted of four subplots of which one was not treated with fertiliser N and the others with fertiliser N application time/mode treatments. In series B and series C experiments each main plot consisted of eight subplots, one of which was not treated with fertiliser N and the other subplots each received one of the seven fertiliser N application time/mode treatments. The fertiliser N application time/mode treatments were randomly allocated to the subplots.

In each series of experiments fertiliser N application time treatments were factorially combined with fertiliser N application mode treatments. In series A experiments in which the total quantity of each fertiliser N application rate (kg N ha^{-1}) was applied in one dressing at early tillering (GS 22–23) and at early stem elongation (GS 32–33) and divided equally between the two application times (Table 1), there were three different application time/mode treatments. In series B and series C experiments the total quantity of each fertiliser N application rate (kg N ha^{-1}) was applied in one dressing at each of three application times (Table 1) and was divided equally two ways and three ways between the application times, giving seven different application time/mode treatments.

When wheat seedlings were fully emerged (GS 11), permanent quadrats were established in each plot. In series A and series B experiments six permanent quadrats, each 33.3 cm long and 30 cm wide were pegged lengthwise across the two middle drill rows of each plot. In series C experiments two permanent quadrats, each 200 cm long and 30 cm wide were similarly located in each plot.

The mature wheat crops (GS 91–92) were harvested in late summer (late January/February), when all wheat plants in each permanent quadrat were taken for measurements of plant grain yield components, plant grain yield, crop grain yield components, and crop grain yield.

After barn conditioning for several weeks, the whole wheat plants taken from each permanent quadrat were dissected to obtain weights and/or counts of the wheat plant grain yield components plant straw (g plant^{-1}), plant ears (ears plant^{-1}), ear grains (grains ear^{-1}), mean grain weight (mg grain^{-1}), and plant grain yield (g plant^{-1}). Likewise measures of the wheat crop grain yield components, namely crop straw (kg m^{-2}), crop ears (ears m^{-2}), crop grains (grains m^{-2}), and crop grain yield (t ha^{-1}) were obtained from the measurements of the whole wheat plants taken from the permanent quadrats.

Measurements of wheat populations, plant grain yield components, plant grain yields, crop grain yield components, and crop grain yields for each field experiment were statistically examined using analysis of variance. Additionally, for each series of experiments, equivalent data from the six or seven field experiments comprising each series, were combined and subjected to analysis of variance. In each analysis of variance for each series of experiments the six or seven field experiments were treated as replicates and appropriate factorial configurations were observed.

In the course of analyses of variance of data obtained from each field experiment included in series B and series C, two orthogonal contrasts were used to compare effects among the seven fertiliser N application time/mode treatments. They were: (1) trends in effects or responses to times of fertiliser N application; and (2) the effects of dividing or splitting the total quantities or rates of fertiliser N among two and three part-applications. For contrast (1), the three fertiliser N application times were taken to be equally spaced in time and each divided or split application was assigned an average value for the two or three times at which part-applications were made. A linear contrast was then calculated using the seven application times to summarise the linear trend for "lateness" of fertiliser N application.

In contrast (2), both the divided or split applications and the undivided or single applications were averaged and the average values compared. Since the two application mode averages had equal value for timing, contrasts of fertiliser N application times and fertiliser N application modes were not confounded. Similar, though more simple, contrasts were used in the analyses of variance of the data obtained from each Series A experiment and the combined data of Series A experiments.

RESULTS

General

Weather conditions differed among experimental sites, but variations in weather between the three wheat cropping years tended to be greater. In both the 1981/82 and 1982/83 wheat cropping years, late autumn and winter monthly rainfalls were similar to monthly potential evapotranspirations, whereas late spring and summer monthly rainfalls were markedly less than monthly potential evapotranspirations. Summer conditions tended to be more droughty in 1982/83 than in 1981/82. Cooler and damper climatic conditions were experienced in 1983/84, in that monthly rainfall was greater than monthly potential evapotranspiration throughout the late autumn and winter, and in the spring and summer months was barely exceeded by monthly potential evapotranspiration.

All experimental wheat crops established well, except that in experiment 5 wheat plant establishment was suppressed by heavy rain which waterlogged the seedbed shortly after seeding.

Generally the experimental wheat crops remained weed free. However, dense mixed populations of wild oats established at the sites of experiments 1, 14, 16, and 18.

Most experimental wheat crops remained free from root and stem rots. Nonetheless, many small, scattered clumps of wheat plants in the crop of experiment 7 became infected with take-all (*Gaeumannomyces graminis* (Sarr.) von Arx and Olivier var. *tritici* Walker). Infections of wheat stems, leaves, and ears by other pathogens such as stripe rust (*Puccinia striiformis* West.) appeared in some experimental crops but, apart from those of experiments 14, 16, and 18, were effectively controlled by application of a systemic fungicide.

In Experiment 6, wheat plants established from the highest rate of wheat seed (495 seeds m^{-2}) and treated with the high rate of fertiliser N (140 kg N ha^{-1}) lodged severely. Lodging of wheat plants did not occur in other field experiments.

Wheat seed rate

Field establishments of wheat plants (wheat plants $m^{-2} \times 100$/wheat seeds m^{-2}) differed within and between field experiments. In general, field establishment of wheat plants was close to 100% at the lower rates of seeding (165 seeds m^{-2} or fewer), but above the nominated base rates, declined with each increment in wheat seed rate. Despite the reductions in field establishments of wheat plants, wheat population became significantly more dense with each increment in wheat seed rate in all experiments and in each series of experiments ($P < 0.001$) (Table 2).

The effects on wheat grain yield components caused by increases in wheat seed rate above the base rates differed between plant grain yield components and crop grain yield components. In no fewer than 18 field experiments the plant grain yield components plant straw, plant ears, and ear grains were significantly reduced ($P < 0.05$) by increases in wheat seed rate. Mean grain weight which was not significantly affected in 12 field experiments, was significantly enhanced in one field experiment and significantly depressed ($P < 0.05$) in six other field experiments by increases in wheat seed rate. Overall, increases in wheat seed rate significantly reduced plant straw, plant ears, ear grains, and mean grain weight in series A, B, and C experiments (Table 2). Wheat plant grain yield was significantly reduced ($P < 0.05$) in all 19 field experiments and overall, in series A, B, and C experiments by increased wheat seed rate (Table 2).

In individual field experiments, increase in wheat seed rate had irregular effects (frequently positive though not always statistically significant) on the wheat crop grain yield components crop straw, crop ears, and crop grains. Overall, crop straw yield in series A and C experiments, the numbers of crop ears in each series of experiments, and the numbers of crop grains in series C experiments were significantly boosted by increased wheat seed rate (Table 2). Wheat crop grain yield was not significantly enhanced by sowing high rates of wheat seed in 12 field experiments. However, in seven field experiments which were either sown late, in midwinter (experiments 11, 12, and 14), or exposed to poor soil conditions (experiments 4 and 5), or suffered from ineffective control of weeds and/or fungal infections (experiments 14, 16, and 18), wheat crop grain yield was significantly improved by high wheat seed rate. Overall, wheat crop grain yield was significantly enhanced ($P < 0.01$) by increase in the rate of wheat seed only in series C experiments (Table 2).

Table 2 Main effects of wheat (*Triticum aestivum*) seed rate for series A, B, and C experiments. (NS, not significant.)

	Wheat seed rate (seeds m^{-2})	Wheat population (plants m^{-2})	Plant straw (g $plant^{-1}$)	Plant ears (ears $plant^{-1}$)	Ear grains (grains ear^{-1})	Mean grain weight (mg $grain^{-1}$)	Plant grain yield (g $plant^{-1}$)	Crop straw (kg m^{-2})	Crop ears (ears m^{-2})	Crop grains (grains m^{-2})	Crop grain yield (t ha^{-1})
Series A experiments											
	83	83	11.7	5.6	33.5	42.2	8.13	0.99	481	15820	6.77
	165	153	6.9	3.6	30.0	41.3	4.55	1.03	547	16400	6.80
	247	224	4.9	2.8	27.3	41.3	3.21	1.08	619	16910	7.04
	330	281	3.7	2.2	26.0	41.2	2.35	1.04	622	16160	6.61
	495	416	2.9	1.6	24.9	40.4	1.67	1.14	662	16500	6.66
LSD(5%)		13	0.6	0.2	0.6	0.9	0.48	0.05	28	850	0.40
Significance of contrasts											
Rate (linear)		$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	NS	NS
Rate (quadratic)		NS	$P < 0.001$	$P < 0.001$	$P < 0.001$	NS	$P < 0.001$	NS	$P < 0.001$	NS	NS
Series B experiments											
	165	189	5.0	2.9	29.1	43.9	3.74	0.91	530	15640	6.75
	330	301	3.3	2.1	26.7	42.8	2.41	0.95	605	16210	6.89
LSD(5%)		10	0.2	0.1	0.4	0.6	0.17	0.04	21	580	0.24
Significance of rate effect		$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	NS	$P < 0.001$	NS	NS
Series C experiments											
	220	205	2.9	2.7	28.9	48.4	3.81	0.59	543	15700	7.62
	339	308	2.0	2.0	27.4	48.1	2.60	0.62	597	16350	7.88
LSD(5%)		6	0.1	0.1	0.4	0.3	0.11	0.01	15	360	0.18
Significance of rate effect		$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.05$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.01$

Fertiliser nitrogen

Wheat populations which established in each field experiment and in each series of experiments were not significantly affected by the application of fertiliser N (Table 3).

Apart from mean grain weight, plant grain yield components and crop grain yield components were significantly improved ($P < 0.05$) in most field experiments and overall in each series of experiments by applied fertiliser N (Table 3). Mean grain weight which was significantly enhanced ($P < 0.05$) in two field experiments, was not significantly affected in four field experiments and significantly depressed in the other 13 field experiments by applied fertiliser N. Overall, in series A, B, and C experiments mean grain weight was significantly reduced by applied fertiliser N (Table 3).

Wheat plant grain yield and crop grain yield were significantly improved by applied fertiliser N in most field experiments and in each series of experiments (Table 3).

Fertiliser N application rate

Wheat populations which established in 13 field experiments were not significantly affected by the total quantity or rate of fertiliser N applied. Nonetheless, in experiments 5, 7, and 15 significantly greater numbers of wheat plants, and in experiments 10, 17, and 19 significantly fewer wheat plants established where the high rate of fertiliser N (either 120 or 140 kg N ha^{-1}) was applied. Overall, wheat populations in each series of experiments were not significantly affected by fertiliser N application rate (Table 3).

In individual field experiments, the high rate of fertiliser N (either 120 or 140 kg N ha^{-1}) had greater effects on plant grain yield components and crop grain yield components than the contrasted low rate, but only half of the differences between effects induced by each application rate achieved statistical significance. However, analyses of data combined for each series of experiments showed overall effects on plant grain yield components and crop grain yield components induced by each rate of fertiliser N in each series of experiments were much less variable than those measured in individual field experiments. In series B and series C experiments plant ears and ear grains, and in each series of experiments crop straw, crop ears, and crop grains were improved more significantly by the high rate of fertiliser N than by the low rate (Table 3). Overall reductions of mean grain weight induced by the high rate of fertiliser N were significantly more severe in series A, B, and C experiments than those caused by the low rate.

Wheat plant grain yield in eight field experiments and crop grain yield in 10 field experiments were improved more significantly ($P < 0.05$) by the high rate of fertiliser N (either 120 or 140 kg N ha^{-1}) than by the low rate. Overall, plant grain yield in Series C experiments and crop grain yield in both series B and C experiments were increased more significantly by the high rate of fertiliser N than by the low rate (Table 3).

In all comparisons of positive effects caused by each rate of applied fertiliser N, the additional effect induced by the second increment of fertiliser N supplied in the high application rate was much smaller than the corresponding effect induced by the initial increment.

Fertiliser N application time

In each field experiment and in each series of experiments (Table 4) wheat populations were not significantly affected by fertiliser N application time.

Generally, in most field experiments and in each series of experiments, responses by wheat plant grain yield components and crop grain yield components to equal quantities of fertiliser N applied at different times or stages of wheat growth did not differ significantly. Nonetheless, in seven field experiments fertiliser N applied at early tillering (GS 22–23), or earlier, produced significantly higher yields of plant straw and crop straw and significantly greater numbers of plant ears and crop ears than an equal quantity of fertiliser N applied later at early stem elongation (GS 32–33). In contrast, in nine field experiments, fertiliser N applied at early stem elongation induced significantly greater numbers of ear grains than an equal quantity of fertiliser N applied earlier. Reductions in mean grain weight induced by fertiliser N applied late, at early stem elongation, in six field experiments were significantly smaller ($P < 0.05$) than reductions caused by earlier applications. Overall, differences between effects on plant ears, crop straw, and crop ears caused by equal quantities of fertiliser N applied at different times or stages of wheat growth showed as statistically significant effects ($P < 0.05$) in both series A and B experiments (Table 4).

Neither wheat plant grain yield responses nor wheat crop grain yield responses to equal quantities of fertiliser N applied at different times or stages of wheat growth differed significantly in 17 field experiments and overall, in each series of experiments (Table 4).

Table 3 Main effects of applied fertiliser nitrogen (N) and fertiliser N application rates for series A, B, and C experiments. For each series of experiments two least significant differences (LSD) are given for each wheat (*Triticum aestivum*) measurement. LSD[A] is for comparison of fertiliser N nil effect and the mean effect of the low and high rates of fertiliser N. LSD[B] is for comparison of the effects of the low rate and the high rate of fertiliser N. (NS, not significant.)

	Rate of fertiliser N (kg N ha^{-1})	Wheat population (plants m^{-2})	Plant straw (g $plant^{-1}$)	Plant ears (ears $plant^{-1}$)	Ear grains (grains ear^{-1})	Mean grain weight (mg $grain^{-1}$)	Plant grain yield (g $plant^{-1}$)	Crop straw (kg m^{-2})	Crop ears (ears m^{-2})	Crop grains (grains m^{-2})	Crop grain yield (t ha^{-1})
Series A experiments											
	Nil	233	5.1	2.6	27.1	44.3	3.45	0.90	486	13040	5.83
	70	229	6.2	3.2	28.4	43.1	4.23	1.06	582	16230	7.04
	140	234	6.1	3.3	28.7	38.5	3.91	1.10	624	17590	6.83
LSD(5%)[A]		12	0.5	0.2	0.5	0.8	0.43	0.05	25	770	0.36
LSD(5%)[B]		9	0.4	0.1	0.4	0.6	0.33	0.04	19	580	0.27
Significance of contrasts											
Nil versus Some		NS	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.01$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$
Low versus High		NS	NS	NS	NS	$P < 0.001$	NS	$P < 0.05$	$P < 0.001$	$P < 0.001$	NS
Series B experiments											
	Nil	243	3.1	1.9	24.9	46.1	2.34	0.69	439	11200	5.16
	70	244	4.2	2.5	27.7	44.0	3.04	0.91	550	15280	6.67
	140	246	4.4	2.6	28.6	42.3	3.21	0.98	602	17250	7.21
LSD(5%)[A]		21	0.5	0.2	0.9	1.1	0.33	0.07	42	1160	0.48
LSD(5%)[B]		11	0.3	0.1	0.5	0.6	0.17	0.04	21	600	0.25
Significance of contrasts											
Nil versus Some		NS	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$
Low versus High		NS	NS	$P < 0.01$	$P < 0.001$	$P < 0.001$	NS	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$
Series C experiments											
	Nil	253	2.1	2.0	26.0	48.8	2.60	0.51	476	12620	6.19
	60	259	2.4	2.3	27.6	48.5	3.07	0.59	556	15430	7.50
	120	255	2.6	2.5	29.0	47.9	3.43	0.63	598	17110	8.21
LSD(5%)[A]		12	0.2	0.1	0.7	0.6	0.22	0.03	30	720	0.35
LSD(5%)[B]		6	0.1	0.1	0.4	0.3	0.11	0.01	15	370	0.18
Significance of contrasts											
Nil versus Some		NS	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.05$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$
Low versus High		NS	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$

Table 4 Main effects of fertiliser nitrogen (N) application times and fertiliser N application modes for series A, B, and C experiments. For each series of experiments two least significant differences (LSD) are given for each wheat (*Triticum aestivum*) measurement. LSD[A] is for comparison of fertiliser N application times. LSD[B] is for comparison of fertiliser N application modes. (NS, not significant.)

Fertiliser N application regime (timing and splitting)	Wheat population (plants m^{-2})	Plant straw (g $plant^{-1}$)	Plant ears (ears $plant^{-1}$)	Ear grains (grains ear^{-1})	Mean grain weight (mg $grain^{-1}$)	Plant grain yield (g $plant^{-1}$)	Crop straw (kg m^{-2})	Crop ears (ears m^{-2})	Crop grains (grains m^{-2})	Crop grain yield (t ha^{-1})
Series A experiments										
Nil N	233	5.1	2.6	27.1	44.3	3.45	0.90	485	13 040	5.83
Single at GS 22	230	6.3	3.4	28.1	40.6	4.11	1.11	613	16 980	6.94
Single at GS 32	233	6.0	3.1	29.1	40.9	4.05	1.05	582	16 650	6.87
Split (22 and 32)	231	6.2	3.3	28.4	40.9	4.05	1.09	613	17 090	6.99
LSD[A](5%)	11	0.5	0.2	0.5	0.8	0.40	0.04	23	710	0.33
LSD[B](5%)	10	0.4	0.2	0.4	0.7	0.35	0.03	20	610	0.29
Significance of contrasts										
Lateness of N	NS	NS	$P < 0.01$	$P < 0.001$	NS	NS	$P < 0.01$	$P < 0.01$	NS	NS
Splitting of N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Series B experiments										
Nil N	243	3.1	1.9	24.9	46.1	2.34	0.69	438	11 200	5.16
Single at GS 11	246	4.3	2.6	27.1	43.3	3.08	0.97	586	15 940	6.83
Single at GS 22	246	4.3	2.6	28.4	42.9	3.22	0.96	593	16 860	7.16
Single at GS 32	242	3.8	2.3	28.5	44.3	2.97	0.84	521	14 990	6.54
Split (11 and 22)	241	4.5	2.7	27.6	42.3	3.17	0.98	598	16 540	6.94
Split (11 and 32)	243	4.2	2.5	28.1	43.3	3.13	0.93	565	15 980	6.87
Split (22 and 32)	250	4.3	2.5	29.0	42.4	3.15	0.98	588	17 100	7.17
Split (11,22,32)	247	4.4	2.5	28.1	43.6	3.18	0.97	582	16 430	7.06
LSD[A](5%)	20	0.5	0.2	0.8	1.1	0.32	0.07	40	1120	0.46
LSD[B](5%)	11	0.3	0.1	0.4	0.6	0.17	0.04	22	600	0.25
Significance of contrasts										
Lateness of N	NS	$P < 0.05$	$P < 0.05$	$P < 0.001$	NS	NS	$P < 0.01$	$P < 0.01$	NS	NS
Splitting of N	NS	NS	NS	NS	NS	NS	$P < 0.05$	NS	NS	NS
Series C experiments										
Nil N	253	2.1	2.0	26.0	48.8	2.60	0.51	476	12 620	6.19
Single at GS 00	261	2.5	2.3	28.4	48.3	3.23	0.62	581	16 410	7.95
Single at GS 22	252	2.6	2.4	28.7	47.9	3.33	0.62	581	16 520	7.94
Single at GS 32	257	2.4	2.3	28.7	48.3	3.28	0.59	571	16 360	7.94
Split (00 and 22)	256	2.5	2.4	27.9	48.1	3.22	0.62	579	16 140	7.79
Split (00 and 32)	260	2.5	2.4	28.0	48.1	3.19	0.61	578	16 130	7.76
Split (22 and 32)	255	2.5	2.4	28.6	48.1	3.31	0.60	577	16 420	7.93
Split (00, 22, 32)	258	2.5	2.3	28.0	48.3	3.19	0.61	571	15 910	7.69
LSD[A](5%)	12	0.2	0.1	0.7	0.5	0.21	0.03	29	700	0.34
LSD[B](5%)	10	0.2	0.1	0.6	0.4	0.18	0.03	25	610	0.29
Significance of contrasts										
Lateness of N	NS	NS	NS	NS	NS	NS	$P < 0.05$	NS	NS	NS
Splitting of N	NS	NS	NS	$P < 0.05$	NS	NS	NS	NS	NS	NS

Fertiliser N application mode

Equal division or splitting of the total quantity of each fertiliser N application rate between two or three part-applications, made at the different stages of wheat growth, had small non-significant effects on wheat population both in individual field experiments and overall, in each series of experiments (Table 4). Likewise, in at least 16 field experiments and overall, in each series of experiments, wheat plant grain yield components, plant grain yield, crop grain yield components, and crop grain yield were not significantly improved by division of fertiliser N applications (Table 4).

Interactions

Few two-factor and three-factor interactions achieved statistical significance ($P < 0.05$) in either individual field experiments or each series of experiments (Table 5). Of the six two-factor and two three-factor interactions tested, only wheat seed rate × fertiliser N and wheat seed rate × fertiliser N application rate interactions attained statistical significance more frequently than the nil effect rate (5%). In view of the small numbers of statistically significant interactions and their extreme variability, only wheat crop grain yield data for wheat seed rate × fertiliser N application rate interactions calculated for each series of experiments are presented (Table 6). They are relevant to discussion of the proposal that the rate of fertiliser N applied to wheat be reduced with increase in wheat population.

DISCUSSION

The field experiments were undertaken to quantify effects on wheat crop grain yield caused by sowing a high rate of wheat seed and treating the resultant dense population of wheat plants with divided applications of a high rate of fertiliser N. When near-normal growing conditions were experienced, the establishment of a dense wheat population generally failed to improve crop grain yield, especially in autumn-sown wheat, and the division or splitting of the total quantity of fertiliser N used between two or three part-applications failed to improve the efficacy of applied fertiliser N and to enhance crop grain yield.

The wheat cultivar ('Rongotea') used in the experimental work is no longer in common commercial use. Nonetheless, the authors consider their conclusions regarding the effects of sowing a high rate of wheat seed and establishing a dense wheat population apply equally to wheat cultivars currently

Table 5 Numbers of wheat (*Triticum aestivum*) populations, plant grain yield components, plant grain yields, crop grain yield components, and crop grain yields involved in statistically significant ($P < 0.05$) two factor and three-factor interactions in all 19 field experiments. (Factor abbreviations: WSR, wheat seed rate; FN, applied fertiliser nitrogen (N); FNAR, fertiliser N application rate; FNAT, fertiliser N application time; and FNAM, fertiliser N application mode.)

Wheat trait	Two-factor interactions							Three-factor interactions		
	WSR × FN	WSR × FNAR	WSR × FNAT	WSR × FNAM	FNAR × FNAT	FNAR × FNAM	% of total	WSR × FNAR × FNAT	WSR × FNAR × FNAM	% of total
Wheat population	4	6	0	0	0	1	9.6	0	0	0
Plant straw	5	6	3	2	0	2	15.8	0	0	0
Plant ears	6	9	2	1	1	1	17.8	1	0	2.6
Ear grains	6	5	1	1	1	0	12.3	0	0	0
Mean grain weight	2	2	0	0	2	0	5.3	0	1	2.6
Plant grain yield	5	5	0	3	0	0	11.4	2	0	5.2
Crop straw	2	5	2	0	1	0	8.8	0	1	2.6
Crop ears	5	7	2	0	0	1	13.2	0	1	2.6
Crop grains	4	3	1	1	1	0	8.8	1	0	2.6
Crop grain yield	3	5	0	0	0	0	7.0	0	0	0
% of total	22.1	28.9	5.8	4.2	3.2	2.6		2.1	4.6	

Table 6 Wheat (*Triticum aestivum*) crop grain yields (t ha^{-1}) in wheat seed rate × fertiliser nitrogen (N) application rate interactions for series A, B, and C experiments. For each series of experiments interactions between polynomial contrasts for wheat seed rate and the two fertiliser N contrasts viz "nil versus some" and "low application rate versus high application rate" were not statistically significant. Each least significant difference (LSD) given in the table applies only to comparisons of mean values in the column to which it is assigned.

Seed rate (seeds m^{-2})	Nil N	60–70 kg N ha^{-1}	120–140 kg N ha^{-1}
Series A experiments			
83	6.17	7.06	6.68
165	5.99	7.01	6.86
247	5.97	7.17	7.27
330	5.51	6.95	6.64
495	5.50	7.01	6.69
LSD(5%)	1.05	0.61	0.61
Series B experiments			
165	5.25	6.59	7.14
330	5.07	6.75	7.29
LSD(5%)	0.92	0.35	0.35
Series C experiments			
220	6.16	7.39	8.05
339	6.22	7.62	8.38
LSD(5%)	0.69	0.26	0.26

available. That view is confirmed by recent investigations into optimum seeding rates for contemporary wheat cultivars (Anon. 2001).

Wheat populations which established from equivalent rates of wheat seed differed among experimental sites, showing that despite precautions to minimise variation, field establishments of wheat plants were affected by local environmental conditions effective at the time of seeding and immediately after. Although field establishments of wheat plants generally declined with increases in wheat seed rate beyond each base rate, wheat populations became more dense and, therefore, more crowded with each increment in seed rate. Irrespective of speculations regarding possible causes for the reductions in field establishments of wheat plants with increase in wheat seed rate (such as overcrowding of germinating wheat seeds), at high rates of wheat seed some seeds failed to produce wheat plants and, therefore, were needlessly sown and wasted.

In each field experiment, sowings of wheat seed at rates greater than the nominated base rates boosted wheat populations, reduced each plant grain yield component, depressed plant grain yield, improved some crop grain yield components and, mostly, failed to enhance crop grain yield. These effects parallel those reported earlier for wheat (Puckridge & Donald 1967; Darwinkel 1978), barley (Kirby 1967), and oats (Jones & Hayes 1967). The negative responses by wheat plants to increases in wheat seed rate and wheat population closely resemble the "self-thinning" response proposed by Westoby (1984) who noted some establishing plants, in overcrowded populations, die as a consequence of interplant competition for inadequate supplies of essential plant growth factors such as sunlight, moisture, and mineral nutrients. Although losses of wheat plants from the experimental crops could not be determined precisely on account of the difficulties of identifying individual plants in the more dense populations, the self-thinning response presented as significant reductions in the numbers and/or sizes of plant grain yield components and plant grain yield. The similarity of reductions in wheat plant grain yield components and plant grain yield to self-thinning suggests that the establishment of overcrowded wheat populations effectively reduces mean supplies of essential plant growth factors available to wheat plants which respond to that stress by producing fewer and/or smaller plant grain yield components and lower plant grain yield.

Although the experimental wheat crops did not appear critically stressed throughout all 9 months of each wheat cropping year, there were periods when stress prevailed. In the more crowded wheat populations plants were more severely shaded by neighbouring plants, especially at later stages of growth. Monthly rainfall data and calculations of monthly potential evapotranspiration indicate wheat plants were seriously stressed by inadequate supplies of moisture, especially in December and January. The generally positive effects on crop grain yield induced by applications of fertiliser N suggest an inadequate supply of plant-available N in soil was another effective stress. Environmental conditions at all experimental sites were conducive to self-thinning, especially in dense wheat populations.

Increased wheat seed rate and the establishment of a more dense wheat population induced changes in the structures of wheat plants and wheat crops. In series A and B experiments, wheat plants comprising crops established from the common base seed rate (165 seeds m^{-2}) had a higher proportion of tiller shoots (mean main shoot: tiller shoot ratio 1:2.38) than wheat plants which made up the more dense crops established from the common high seed rate of 330 seeds m^{-2} (mean main shoot:tiller shoot ratio 1:1.04). A similar effect was seen in series C experiments in that the mean main shoot: tiller shoot ratio (1:1.70) for plants established from the low seed rate of 220 seeds m^{-2} was greater than the mean main shoot:tiller shoot ratio (1:0.97) for plants established from the high seed rate (345 seeds m^{-2}). Since main shoots and first tiller shoots are reported to have greater potential for higher grain yield than lower order tiller shoots (Thorne & Wood 1988), dense wheat crops having proportionally more main and first tiller shoots and fewer lower order tiller shoots could be expected to yield more grain than sparse crops. The higher grain yields anticipated from the more dense wheat crops were not realised in most field experiments and overall in two of the three series of experiments reported here.

Early investigations into the relationship between wheat crop grain yield and either wheat seed rate or wheat population concluded wheat crop grain yield varied little over wide ranges of wheat seed rate and/or wheat population and that the relationship could be expressed as a shallow parabolic curve (Hudson 1941; Holliday 1960). The absence of significant positive crop grain yield responses to increased wheat seed rate and/or wheat population in 12 field experiments and overall in two series of experiments, confirms the earlier conclusions and can be explained as negative responses by wheat plant grain yield components to increase in wheat population. Nonetheless, in series A experiments crop grain yield responses to increases in wheat seed rate ranged from a positive straight line (experiments 4 and 5), to a parabolic curve (experiments 1 and 3), to a negative straight line (experiments 2 and 6).

Since wheat growth interacts with the local environment, models proposed for the relationship between wheat crop grain yield and either wheat seed rate or wheat population need to take into account variation induced by local growing conditions (Bleasdale & Nelder 1960). In the seven field experiments which suffered environmental misadventure such as winter seeding (experiments 11, 12, and 16), unfavourable soil conditions (experiments 5 and 10), and weed competition and inadequately controlled fungal infections (experiments 14, 16, and 18), wheat crop grain yield was significantly improved by sowing a high rate of wheat seed and establishing a dense wheat population. Even though crop grain yield was significantly improved by the use of a high rate of wheat seed and the establishment of a dense wheat population in at least one field experiment in each series of experiments, overall wheat crop grain yield was significantly enhanced only in series C. The absence of positive overall effects in series A and B experiments may have been the result of wider data variation in those series. However, apart from the more regular application of irrigation water, growing conditions experienced by series C experiments tended to be less favourable more frequently.

Locally, the poorer crop grain yield of late-sown wheat has been attributed to the production of fewer tillers and ears by individual wheat plants and presumed to be remedied by sowing a high rate of wheat seed and establishing a dense wheat crop (Hadfield 1950). The compensatory effects of high seed rate and dense wheat population on crop grain yield in late-sown wheat showed in experiments 11, 12, and 16 in which the more dense wheat populations, established from the high rate of seed, produced significantly higher numbers of crop ears and crop grains, and significantly superior crop grain yields. In contrast in autumn-sown experiments, the establishment of dense wheat populations usually resulted in small, non-significant increases in the numbers of crop ears and crop grains and non-significant improvements in crop grain yield. Information about responses by wheat plant grain yield components and crop grain yield components to variation in environmental factors such as weather and agronomic practices is likely to lead to an improved understanding of the development of crop grain yield in wheat (Gallagher & Biscoe 1978).

In addition to their beneficial effects on crop grain yield, fertiliser N treatments were tested to establish whether wheat responses to applied fertiliser N vary between application times, application modes, and wheat populations. The field experiments were purposely located on sites previously cultivated successively with several arable crops so that the soils would lack adequate supplies of plant-available N. In general, applied fertiliser N significantly enhanced all wheat plant grain yield components (except mean grain weight which was significantly reduced), plant grain yield, crop grain yield components, and crop grain yield in each field experiment and in each series of experiments. The positive responses to fertiliser N confirmed pre-seeding expectations that the soils on the experimental sites were deficient in plant-available N.

Generally, establishments of wheat populations were not affected by applied fertiliser N. Although negative effects on the establishment of wheat populations caused by applied fertiliser N have been reported elsewhere (Feyter & Cossens 1977), germination injury in the local field experiments was simply avoided by broadcasting the N fertiliser onto the surface of the seedbed after seeding rather than drilling it in contact with the wheat seed.

Significant reductions in mean grain weight resulted from the application of fertiliser N. Analyses of development and growth in Canterbury wheat crops show grain filling occurs in midsummer (January) when the crops are commonly stressed by high evapotranspiration and low soil moisture (Heine & Ryu 1980). It is reasonable, therefore, to suggest that the significantly greater numbers of ear grains and crop grains induced by applied fertiliser N exacerbated competition among filling grains for inadequate supplies of soil moisture, and thereby caused a form of self-thinning which presented as lower mean grain weights. That explanation is reinforced by the smaller reductions in mean grain weight measured in the more adequately irrigated series C experiments.

The rates of fertiliser N or total quantities applied were selected in light of local experiences (Stephen et al. 1983) which showed a moderate quantity, commonly less than 100 kg N ha^{-1}, had large positive effects on wheat growth and crop grain yield and that heavier applications were more beneficial only infrequently. In the field experiments detailed here the low rate of fertiliser N (60 or 70 kg N ha^{-1}) caused a moderately large positive response in wheat crop grain yield (on average 1.34 t ha^{-1}) and although the second increment of fertiliser N supplied in the high application rate (120 or 140 kg N ha^{-1}) induced an additional crop grain yield response it was much smaller (on average 0.34 t ha^{-1}). These results suggest applications of high rates of fertiliser N to Canterbury wheat crops are not warranted.

Fertiliser N application times or stages of wheat growth at which equal rates of fertiliser N were applied to the experimental wheat crops, were chosen to test a local assertion that fertiliser N applied at early tillering (GS 22–23) is more effective than fertiliser N applied either earlier or later. In the field experiments, the numbers of plant ears and crop ears were generally increased more by early application of fertiliser N than by late application at early stem elongation (GS 32–33). However, the disadvantage of fewer plant ears and crop ears associated with the late application of fertiliser N was partly offset by greater improvement in the numbers of ear grains. As a consequence of these compensatory effects neither wheat plant grain yield nor wheat crop grain yield was significantly affected by the timing of fertiliser N applications.

Generally, wheat populations, plant grain yield components, plant grain yield, crop grain yield components, and crop grain yield did not vary significantly between the two modes of fertiliser N application tested. The absence of superior positive responses to divided or split applications of fertiliser N contrasts with results reported overseas (Dilz et al. 1982; Strong 1982). The explanation for the superior responses to divided applications of fertiliser N in overseas work is simply that the total quantities of fertiliser N supplied in divided applications were greater than the total quantities supplied in contrasted single applications. In that way, fertiliser N application mode treatments were confounded with fertiliser N application rate treatments making it impossible to distinguish between responses caused by application rates and those induced by application modes. It seems probable that the absence of superior wheat crop grain yield responses to divided applications of fertiliser N in the field experiments detailed here was the result of the general absence of effects associated with fertiliser N application time and to the greater effects of fertiliser N application rate.

The suggestion that fertiliser N application rate be varied inversely with wheat population was examined in each field experiment and in each series of experiments by testing the statistical significance of differences between wheat crop grain yields in wheat seed rate × fertiliser N application rate interactions. In 14 field experiments and overall in each experimental series, the wheat seed rate × fertiliser N application rate interaction failed to achieve statistical significance ($P < 0.05$) (Tables 5 and 6).

Since wheat seed rate and wheat population were directly related in most field experiments and in each series of experiments it is reasonable to conclude there is no substantial reason to vary, inversely, fertiliser N application rate with wheat population. Nonetheless, the occurrence of severe lodging in the dense wheat populations established from the highest rate of seeding (495 seeds m^{-2}), and also treated with the high rate of fertiliser N (120 kg N ha^{-1}) in experiment 6, shows the matter requires consideration. It can be argued that the unexplained occurrence of severe lodging in experiment 6 was unusual but, nonetheless, highlights the futilities of sowing an excessive rate of wheat seed and applying an extravagant quantity of fertiliser N.

In assessing effects of wheat seed rate and fertiliser N treatments on wheat crop grain yield, responses by plant grain yield components, including plant grain yield, and crop grain yield components were analysed. Although consideration of responses by both plant grain yield components and crop grain yield components may appear extravagant, analyses of both provided more satisfactory explanations of treatment effects on wheat growth and crop grain yield.

Application of experimental results to wheat cultivation involves consideration of matters of commercial importance such as grain protein content, mean grain weight, and crop grain yield. Protein contents of wheat grain were not measured, but elsewhere have been shown to be improved to preferred levels by application of a modest quantity of fertiliser N. Mean grain weight which was measured, was generally not affected by sowing a high rate of wheat seed but was regularly depressed in both autumn-sown and winter-sown wheat crops by the application of fertiliser N. Wheat crop grain yield was infrequently enhanced by the use of a high rate of wheat seed and the establishment of a dense wheat population except when unfavourable environmental conditions were experienced. On the other hand, wheat crop grain yield was improved by a single application of a moderate quantity of fertiliser N (60 or 70 kg N ha^{-1}) whereas extra fertiliser N produced little additional response. In view of the general reductions in wheat plant grain yield components and plant grain yield induced by sowing high rates of wheat seed and the depression of mean grain weight by applied fertiliser N, the authors conclude a low rate of wheat seed (165 seeds m^{-2}) and a single spring application of a moderate rate of fertiliser N (90–100 kg N ha^{-1}) are sufficient for the successful cultivation of autumn-sown wheat in Canterbury, New Zealand.

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