Interplot interference distorts yield estimates in spring wheat.

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Abstract:

Research in Europe and the USA indicated that interference between plots in cultivar trials can distort yield and result in misleading conclusions from yield comparisons. Field trials were conducted at Swift Current and Saskatoon in 1993 and 1994 to determine if interplot interference is a concern in the wheat growing region of Saskatchewan. Four spring wheat (Triticum aestivum L.) cultivars, Biggar, Oslo, Genesis, and Glenlea, were grown in four-row plots in a diallel competition treatment design, with the competition treatments applied randomly to each of the eight replications. Generally, yield was distorted from pure stand yield when flanking plots differed for height. On average, yield was reduced 0.34% per centimeter increase in height of the flanking plots, and the reverse occurred when height of the flanking plots was less. Plots of the short cultivars; Biggar or Oslo flanked by the tall cultivars Genesis or Glenlea yielded less than when flanked by themselves, and the reverse occurred when the tall cultivars were flanked by the short cultivars. Interplot interference affected spike density in the same fashion, did not significantly affect height, and was inconsistent with regards to kernel weight. It was concluded that when plots differ for height, yield distortion can occur in the Saskatchewan wheat growing region.

Full Text:

Interference between plots is a concern when small plots are used in cultivar trials. Small plots are often necessary because of the need to test a large number of genotypes when seed, land, and/or resources are limited. Plant breeders select for genotypes with improved yield, and want this yield improvement to be expressed in commercial production where the cultivar is grown in pure stand. Kempton et al. (1986) investigated the effect of interplot interference on yield from 1.5-m-wide plots of triticale (x Triticosecale Wittmack) and winter wheat cultivars that differed for height. The authors reported a reduction in yield when the flanking plots were taller and a similar increase in yield when the flanking plots were shorter, which agrees with other reports (Baker and Rossnagel, 1988; Aastveit et al., 1989; Goldringer et al., 1994). Consequently, yield comparisons are misleading when genotypes differ for height. With adequate fertility and moisture, the major source of interplot interference is height difference (Fisher, 1979; Austin and Blackwell, 1980). Kempton et al. (1986) pointed out that interplot interference is not minimized by randomization and averaging over replications because the same relative interference effect for a genotype will remain following the removal of block effects.

The majority of published experiments on interplot interference in wheat were conducted in regions with long growing seasons, and on winter wheat which requires a long growing season. The only report of interplot interference in spring wheat on the Canadian prairies is by Baker and Rossnagel (1988). In Western Canada, cultivar trials for spring wheat often contain both semi-dwarf and tall genotypes. The relatively short growing season may not allow time for growth alteration from interplot interference to be a concern, but this has not been established with certainty. The interplot interference experiment of Baker and Rossnagel (1988) with 1.0-m-wide plots raised doubt about this assumption, but the authors were concerned that their experimental design may have confound environmental gradients with estimates of interference effects. The objective of this research was to use a diallel treatment design to determine if interplot interference occurs in other environments in spring wheat cultivar trials conducted in a short growing season.

MATERIALS AND METHODS

The field experiment was conducted at the University of Saskatchewan Kernen Farm at Saskatoon and at the Semiarid Prairie Agricultural Research Centre at Swift Current in 1993 and 1994. A diallel treatment design was used with four spring wheat cultivars that represented the extremes in height for hexaploid wheat grown in Western Canada. Each treatment consisted of three four-row plots, one cultivar in the center plot and flanked on both sides by itself or one of the other three cultivars, for a total of 16 treatments. Of the two tall cultivars, Glenlea (Evans et al., 1972) is taller than Genesis (DePauw et at., 1989), and of the two short cultivars, Oslo (Graf et al., 1990) is shorter than Biggar (DePauw et al., 1991).

The treatments were randomly applied to each of eight replications in a randomized complete block design. Each replication contained a single range of plots, and the replications were adjacent along their long side. Replications were bordered with one plot on each end at Saskatoon, and with six plots on each end at Swift Current. At Swift Current, a 4-m strip of the spring wheat Lancer was seeded along the north and south ranges of the test for wind protection. The plots were seeded with a plot seeder at approximately 270 seeds [m.sup.-2]. Interplot and interrow spacing was 30 cm and rows were oriented north-south. The Saskatoon plots were 3.7 m long and had 1.8-m cultivated alleys between ranges. The plots at Swift Current were trimmed to 3 m with 2-m spring-planted winter wheat alleys between ranges.

Prior to planting at Swift Current in 1993 and 1994, nitrogen (34-0-0) was broadcast at 45 kg [ha.sup.-1], and nitrogen and phosphorus (11-51-0) were broadcast at 20 kg [ha.sup.-1]. At Saskatoon and at Swift Current in 1994, 11-51-0 was applied with the seed at 56 kg [ha.sup.-1]. In 1993, Swift Current was seeded 5 May and Saskatoon was seeded 14 May, and in 1994, Swift Current was seeded 7 May and Saskatoon was seeded 10 May. The seed was planted into moist soil, to a depth of 1.75 cm in 1993 and 2.25 cm in 1994. A mixture of the herbicides tralkoxydim {2-[1-(ethoxyimino)propyl]-3-hydroxy-5-(2, 4,6-trimethylphenyl)-2-cyclohexen-1-one} and bromoxynil (3,5-dibromo-4-hydroxyphenyl cyanide) and MCPA ([(4-chloro-o-tolyl)oxy]-acetic acid) was applied at Swift Current and bromoxynil was applied at Saskatoon at the four- to five-leaf stage for weed control.

Emergence, spike density, grain yield, and kernel weight measurements were taken on the four rows of each center plot. At the three leaf stage, emergence was counted on a one meter section of each row, one meter in from the front edge. Spikes were counted on the same one meter section about one month after heading, and converted to spike density (the number of spikes per square meter). At maturity, three height measurements were taken in each plot, and the average of these measurements was recorded. All plots in each treatment were harvested with a plot combine, one replication at a time. The four rows of the center plots were harvested individually. Kernel weights were determined on a random sample of 200 whole seeds from each row of the center plots.

The analyses of emergence, spike density, kernel weight and yield data were conducted on the average of the four rows, the average of the outside rows, and the average of the inside rows. These three functions of row performance served as indicators of the extent of interference within a plot. Yield and kernel weight for a missing row at Saskatoon in 1993 and a missing row at Swift Current in 1994 were estimated with analysis of covariance.

Because of variation in emergence, it was necessary to investigate if precision would improve if an adjustment for emergence was included in the analyses. Three types of emergence covariates were considered, zero covariates, one covariate or separate covariates for each of the four cultivars. For each plant characteristic and indicator of interplot interference, the standard errors for interference effects from each of the three choices were averaged over the four tests and compared. The variability in emergence affected spike density, but the plants appeared to compensate for this variability by the time grain had filled.

Bartlett's test for heterogeneous errors indicated that the experimental errors among locations and years were heterogeneous for each indicator of interplot interference for each plant characteristic. The combined analyses over locations and years included estimations of separate error terms for each experiment, and were performed with mixed linear models (McLean et al., 1991). The linear model of observation [y.sub.hijk] is the following:

[y.sub.hijk] = [Mu] + [a.sub.h] + [p.sub.i] + [ap.sub.hi] + [b.sub.(hi)j] + [t.sub.k] + [at.sub.hk] + [pt.sub.ik] + [apt.sub.hik] + [e.sub.hijk]

where the overall mean is [Mu], and the effects for years are [a.sub.h], locations are [p.sub.i], year X location interactions are [ap.sub.hi], blocks within each year and location are [b.sub.(hi)j], the 16 interplot interference treatments are [t.sub.k], and treatment interactions with years are [at.sub.hk], with locations are [pt.sub.ik], and with years by locations are [apt.sub.hik]. The experimental unit variation [e.sub.hijk] was assumed to be normally distributed with zero mean and variance [MATHEMATICAL EXPRESSION NOT REPRODUCIBLE IN ASCII].

Because the samples of years, locations, years X locations and blocks were not large enough to give reliable estimates of the variances of these populations, they were considered fixed (Stroup and Mulitze, 1991). When the model is balanced, the conclusions from treatment comparisons are the same regardless of whether years, locations, years X locations, and blocks are considered random or fixed (Robinson, 1991). The samples of interactions of treatments with years, with locations, and with years and locations were large enough to be considered random. Treatments were considered fixed.

The mixed models analyses were performed with SAS PROC MIXED in version 6.09 (SAS Institute Inc., 1992) for the VAX. Random factors were listed in the RANDOM statement, and fixed factors were listed in the MODEL statement. Weighting of each of the four tests for the combined analyses was accomplished with inclusion of the REPEATED statement along with an option for grouping data by tests (REPEATED/GROUP = YEARS X LOCATIONS;). The variance of each random interaction was calculated with restricted maximum likelihood, REML. PROC MIXED takes into account the missing values in the calculation of standard errors and of residual error degrees of freedom. An average standard error of the linear function of each treatment was reported when the data contained missing values.

The combined analyses with PROC MIXED required the use of appropriate starting values for the variances before the default convergence requirements were met. The starting values were listed in the PARMS statement. The initial starting values were the variances for the random interactions from the unweighted combined analysis, and the error variances from the separate analyses of each test (Searle et al., 1992, p. 295). If convergence requirements were not achieved, the variances estimated at the last iteration were used as starting values in the next attempt (F. Giesbrecht, 1995, personal communication). If a number of attempts were unsuccessful, different starting values were tried for variances whose estimates were zero. At the same time, Fisher scoring was tried for the first iteration, and the Newton-Raphson algorithm was used for the remaining iterations (Jennrich and Schluchter, 1986). The one iteration of Fisher scoring was indicated with inclusion of the SCORING option in the PROC MIXED statement.

For each combined analysis, an approximation of Satterthwaite's approximate degrees of freedom was calculated for the appropriate error term of the linear function of the treatments. The approximation of Satterthwaite's approximate degrees was calculated from the ratio of twice the square of the variance of the linear function of the data and the variance of the variance of the linear function, (McLean and Sanders, 1988), as described elsewhere (Clarke, 1996). In our approximation, the coefficients for the four error variances were equal, while PROC MIXED uses coefficients weighted according to the heterogeneity of errors. Since these terms contributed very little to the calculation of degrees of freedom, use of equal weights should provide a close approximation. With equal variances, this method gives an exact estimate of Satterthwaite's approximate degrees of freedom.

To define interplot interference effects, it is useful to expand the single subscript k for each treatment into three subscripts to indicate the components. The response to interplot interference, [c.sub.k'kk'] = [t.sub.k'kk'] - [t.sub.kkk], of the tall cultivar k to interference from the short cultivar k' in flanking plots is the difference in response when flanked by the short plots ([t.sub.k'kk']) and response when flanked by itself ([t.sub.kkk]). Likewise, the response of the short cultivar k' to interference from the tall cultivar k is [c.sub.kk'k] = [t.sub.kk'k] - [t.sub.k'k'k']. If the t-test indicated the response to interplot interference of the tall cultivar of the pair was significantly greater than zero ([H.sub.a]: [c.sub.k'kk'] [is greater than] 0) or response of the short cultivar was significantly less than zero ([H.sub.a]: [c.sub.kk'k] [is less than] 0), interplot interference was assumed to have occurred. The response to interplot interference of each cultivar in each possible cultivar pair was tested to see if the response when cultivar k was flanked by cultivar k' was the same magnitude and of opposite sign to the response when cultivar k' was flanked by cultivar k ([H.sub.o]: [c.sub.k'kk'] = -[c.sub.kk'k]). Under the hypothesis that the response was complementary, the response was averaged to see if it was greater than zero [H.sub.a]: {[[c.sub.k'kk'] + (-[c.sub.kk'k])]/2 [is greater than] 0}.

The average difference in height, 1/2([h.sub.j-1] + [h.sub.j+1]) - [h.sub.j], between flanking plots ([h.sub.j-1] and [h.sub.j+1]) and the center plot ([h.sub.j]) was calculated for each treatment triplet. For each treatment, the means of the average height differences were calculated from the separate analysis of each test, and from the combined analysis of the four tests. The average responses to interplot interference for each treatment from each test and from the combined analysis were regressed on the corresponding average height differences. For each centimeter change in magnitude, the change in yield was expressed as a percent of the overall yield for the corresponding test or of the overall yield over the four tests.

RESULTS AND DISCUSSION

The cultivars differed for height at Swift Current and Saskatoon in 1993 and 1994 (Table 1). Height was not significantly affected by interference between plots, which agrees with experiments conducted by Smith et al. (1970) on oat hill plots, and by Hamblin and Donald (1974) on barley plots. Average height difference varied among the sites and differed for treatments. The cultivar pair Glenlea-Oslo had the largest height difference.

Table 1. Average cultivar height and pure stand yield at Swift Current and Saskatoon in 1993 and 1994 and average over the four tests.

	Swift Current			
	1993		1994	
Cultivar	Height cm	Yield g [m.sup.-1]	Height cm	Yield g [m.sup.-2]
Biggar	81	501	77	371
Oslo	73	420	73	352
Genesis	93	502	93	346
Glenlea	101	411	98	301
[LSD.sub.0.05]	1.4([dagger])	36	1.4	22

	Saskatoon		
	1993		1994
Cultivar	Height cm	Yield g [m.sup.-2]	Height cm

Biggar	88	607	81
Oslo	86	609	73
Genesis	105	573	99
Glenlea	121	514	110
[LSD.sub.0.05]	1.2	37	1.4([dagger])

	Saskatoon 1994	Combined average	
Cultivar	Yield g [m.sup.-2]	Height cm	Yield g [m.sup.-2]
Biggar	534	82	503
Oslo	474	76	464
Genesis	504	98	481
Glenlea	470	108	424
[LSD.sub.0.05]	34([dagger])	3.3([dagger])	52([dagger])

([dagger]) Used average standard error of treatment means because of missing plots.

Interplot interference had a significant effect on plot yield (Table 2). On average, Oslo flanked by Glenlea had the greatest reduction from plot yield in pure stand, and Glenlea flanked by Oslo had a similar gain in pure stand plot yield (Table 2). Glenlea had the greatest effect of the three cultivars in an interplot interference experiment conducted by Baker and Rossnagel (1988). For each centimeter the flanking plots were taller, plot yield decreased on average 1.6 - 0.11 g [m.sup.-2] (p [is less than] 0.0001, adj [r.sup.2] = 0.95) or 0.34% from pure stand yield, and the reverse occurred when flanking plots were shorter. Kempton (1984) surveyed a number of cereal experiments with 1.5 m wide plots and reported a 0.2% positive or negative change from pure stand yield for each centimeter negative or positive change in height.

Table 2. Plot yield response to interplot interference of four spring wheat cultivars tested at Swift Current and at Saskatoon in 1993 and 1994 and combined response.

	Swift Current		Saskatoon
Treatments	1993	1994	1993
	--g [m.sup.2]--		
Genesis-Glenlea-Genesis([dagger])	-18	18	46(**)
Glenlea-Genesis-Glenlea	-17	5	-77(**)
Biggar-Glenlea-Biggar	-16	5	81(**)
Glenlea-Biggar-Glenlea	-31(*)	4	-83(**)
Oslo-Glenlea-Oslo	34(*)	11	92(**)
Glenlea-Oslo-Glenlea	-55(**)	-14	-95(**)
Oslo-Genesis-Oslo	42(*)	1	39(*)
Genesis-Oslo-Genesis	-44(**)	-6	-64(**)
Biggar-Genesis-Biggar	25	18	48(**)
Genesis-Biggar-Genesis	-14	-16	-43(*)
Oslo-Biggar-Oslo	23	8	19
Biggar-Oslo-Biggar	-28	-6	-23
SE([double dagger])	18	11	19

	Saskatoon	
Treatments	1994	Combined
	--g [m.sup.2]--	
Genesis-Glenlea-Genesis ([dagger])	17	16
Glenlea-Genesis-Glenlea	-35(*)	-29
Biggar-Glenlea-Biggar	30(*)	24
Glenlea-Biggar-Glenlea	-59(**)	-41
Oslo-Glenlea-Oslo	34(*)	42

Glenlea-Oslo-Glenlea	-49(**)	-52(*)
Oslo-Genesis-Oslo	62(**)	35
Genesis-Oslo-Genesis	-60(**)	-43
Biggar-Genesis-Biggar	23	28
Genesis-Biggar-Genesis	-46(**)	-29
Oslo-Biggar-Oslo	4	13
Biggar-Oslo-Biggar	8	-12
SE([double dagger])	17([sections])	24([sections])

(*), (**) Magnitude significantly greater than zero at the 0.05 and 0.01 levels of probability, respectively.

([dagger]) Treatment Genesis-Glenlea-Genesis has Glenlea in the center plot and Genesis in the flanking plots.

([double dagger]) SE is standard error.

([sections]) Used average standard error of treatment differences because of missing plots.

The significant variance component for year by location X treatment interaction indicated that the level of interplot interference was affected by the environment. The change from pure stand yield for each centimeter average height difference was -2.81 [+ or -] 0.16 g [m.sup.-2] (-0.49%) (adj [r.sup.2] 2 = 0.96) for Saskatoon in 1993, -1.57 [+ or -] 0.20 g [m.sup.-2] (-0.32%) (adj [r.sup.2] 2 = 0.84) for Saskatoon in 1994, -1.44 [+ or -] 0.31 g [m.sup.-2] (-0.32%) (adj [r.sup.2] = 0.65) for Swift Current in 1993, and -0.43 [+ or -] 0.15 g [m.sup.-2] (-0.12%) (adj [r.sup.2] = 0.40) for Swift Current in 1994 (all P [is less than] 0.005). The environments with highest yield, Swift Current 1993 and Saskatoon 1993 and 1994, had the most interplot interference. The average yield at Saskatoon was 571.9 [+ or -] 3.2 g [m.sup.-2] in 1993 and 491.3 [+ or -] 3.1 g [m.sup.-2] in 1994, while average yield at Swift Current was 452.0 [+ or -] 3.2 g [m.sup.-2] in 1993 and 344.4 [+ or -] 1.9 g [m.sup.-2] in 1994. The yield potential at Swift Current in 1994 was reduced by low rainfall from the end of July to harvest (Table 3). Similarly, Gomez (1972), Hamblin and Rowell (1975), Austin and Blackwell (1980), Kempton et al. (1986), and Aastveit et al. (1989) reported that interplot interference was influenced by the environment, and was greater in sites with high yield potential where adequate water and nutrients are available.

Table 3. Monthly total precipitation (Precip.) and average temperature (Temp.) at Swift Current and Saskatoon in 1993 and 1994.

	Swift Current			
	1993		1994	
	Precip.	Temp.	Precip.	Temp.
	mm	[degrees] C	mm	[degrees] C
May	15	12.2	62	11.8
June	52	14.4	82	15.4
July	107	15.1	16	18.2
August	153	15.8	32	18.1
Total	327		192	

	Saskatoon			
	1993		1994	
	Precip.	Temp.	Precip.	Temp
	mm	[degrees] C	mm	[degrees] C
May	37	11.3	109	11.1
June	58	13.7	90	15.4
July	75	15.2	68	17.5
August	40	15.9	62	16.5
Total	210		329	

The effect of interplot interference on pure stand yield was greater in the outside rows than the inside rows (Table 4). At Swift Current in 1993 and Saskatoon in 1993 and 1994, interference extended significantly to the inside rows, which casts doubt on the effectiveness of using the center two rows of four row plots to estimate pure stand yield (e.g., Jensen and Federer, 1964; Spitters, 1979). Other studies also indicated that interplot interference may extend to the center rows (Hanis et al., 1976; Kempton and Lockwood, 1984).

[TABULAR DATA 4 NOT REPRODUCIBLE IN ASCII]

Of the components of yield examined, interplot interference significantly affected spike density adjusted for plot to plot variation in emergence, and the effect was consistent over Swift Current and Saskatoon in 1993 and 1994. Spike density of the cultivar pair with the greatest height difference, Glenlea-Oslo, was affected the most (Table 5). For each cultivar pair, the magnitude of response to interplot interference when one cultivar was the center plot was not significantly different from the magnitude when the other cultivar was the center plot. For each centimeter increase in height of flanking plots, spike density decreased 0.59 spikes [m.sup.-2] (0.21%) (P [is less than] 0.0002, adj [r.sup.2] = 0.62) from pure stand density. Spike density response to interplot interference was greatest on outside rows, but extended significantly to inside rows with the cultivar pair Glenlea-Oslo (Table 5).

Table 5. Combined spike density response to interplot interference of four spring wheat cultivars; tested at Swift Current and Saskatoon in 1993 and 1994.

Treatment	Plots	Outside rows	Inside rows
	--spikes [m.sup.-2]--		
Genesis-Glenlea-Genesis ([dagger])	4.8	9.6	-0.3
Glenlea-Genesis-Glenlea	-13	-21.8(*)	-7.2
Biggar-Glenlea-Biggar	14.7	17.4(*)	11
Glenlea-Biggar-Glenlea	-12	-15	-7.5
Oslo-Glenlea-Oslo	30.4(**)	40.7(**)	19.9(*)
Glenlea-Oslo-Glenlea	-21.2(*)	-25.6**	-15.4
Oslo-Genesis-Oslo	10.8	3.8	13.8
Genesis-Oslo-Genesis	-16.2(*)	-25.1(**)	-8
Biggar-Genesis-Biggar	-9.8	-9.5	-14.5
Genesis-Biggar-Genesis	6.5	8.6	5.7
Oslo-Biggar-Oslo	1.5	10.3	-5.8
Biggar-Oslo-Biggar	-9	-15.1	-2.9
Average SE([double dagger])	9.1	9.2	10.6

(*), (**) Magnitude significantly greater than zero at the 0.05 and 0.01 levels of probability, respectively.

([dagger]) Treatment Genesis-Glenlea-Genesis has Glenlea in the center plot and Genesis in the flanking plots.

([double dagger]) Used average standard error (SE) of treatment differences because of missing plots.

Our results were not consistent on whether kernel weight is affected by interplot interference. On average, kernel weight was not significantly affected by interplot interference. Kernel weights contained a significant year X location X treatment interaction, and there was a tendency for a significant reduction in kernel weight of the shorter cultivars of the cultivar pairs from interplot interference at Swift Current in 1993 and Saskatoon in 1993 and 1994 (data not shown).

In cultivar trials with a minority of semidwarfs, the semidwarfs would be at the greatest risk of yield distortion, and of being culled during selection. In cooperative cultivar trials, breeders are often trying to differentiate genotypes that differ for yield by 3 to 5%, so a reduction of pure stand yield of a semidwarf by as little as 4% could be enough to eliminate a genotype. If the interplot interference response was -0.34% [cm.sup.-1], flanking plots 12 cm taller than the semidwarf would reduce yield 4% from pure stand yield. At Saskatoon in 1993, Oslo was 35 cm shorter than Glenlea, and a 17% yield reduction from pure stand occurred (Tables 1 and 2).

Yield reductions from interplot interference can be a concern in the Saskatchewan grain growing region. Interplot interference occurred in this experiment, and was also significant in two of the four spring wheat environments tested by Baker and Rossnagel (1988). The environment at a site varies from year to year, so the plant breeder cannot predict the extent of interplot interference in future tests. When height data are available and the genotypes differ for height, yield trials could be arranged by height. If there are not enough of each height class to warrant separate trials, or if it is necessary to compare semidwarfs with tall genotypes, an alternative is grouping of the genotypes within a trial. Talbot et al. (1995), David and Kempton (1996) and David et al. (1996) suggested grouping genotypes of similar height in incomplete blocks in alpha lattice designs. The decrease from pure stand yield for a short cultivar flanked by a tall cultivar was not significantly different from the gain from pure stand yield for the tall cultivar flanked by the short cultivar, so adjustment for interplot interference with one covariate, average height difference, should be sufficient when interplot interference is suspected.

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Abbreviations: REML, restricted maximum likelihood; SE, standard error.

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F.R. Clarke, R. J. Baker,(*) and R. M. DePauw

F.R. Clarke and R.J. Baker, Dep. of Crop Science and Plant Ecology, Univ. of Saskatchewan, Saskatoon, SK S7N 5A8 Canada.; R.M. DePauw, Semiarid Prairie Agric. Res. Centre, Swift Current, SK S9H 3X2 Canada. Part of a PhD thesis submitted by F.R. Clarke. Received 7 April 1997. (*) Corresponding author (bob.baker@usask.ca).

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