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Response of Corn Grain Yield to Spatial and Temporal Variability in Emergence

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ABSTRACT

Potential yield benefits from improving within-row plant spacing variability and plant emergence variability in corn (*Zea mays* L.) production are often questioned by growers. Research was conducted at two locations in south-central Ontario during a 2-yr period to quantify the effects and interactions of plant spacing variability and plant emergence variability on growth and grain yield of corn. Nine treatments were established by hand planting corn rows with repeating six-plant sequences consisting of uniform and nonuniform spacing, even and uneven emergence, and their combinations. Spacing treatments consisted of (i) uniform within-row plant spacing of 20 cm; (ii) one 40-cm gap associated with a double; and (iii) one 60-cm gap associated with a triple in each six-plant sequence. Emergence treatments included uniform early emergence, a two-leaf stage delay, and a four-leaf stage delay for one plant in each six-plant sequence. Only plant emergence variability significantly affected plant height, leaf area index (LAI), dry matter accumulation, and grain yield. Compared with the uniformly early emerged plants, one out of six plants with a two-leaf stage delay in emergence reduced yield by 4%, and one out of six plants with a four-leaf stage delay reduced yield by 8%. Whereas corn plants next to a gap demonstrated compensatory growth, plants adjacent to a late emerging corn plant did not exhibit compensatory growth. These results indicate that corn is more responsive to plant emergence variability than plant spacing variability. Variation in plant emergence reduced yield, whereas variation in within-row spacing did not affect yield, and interactions between the two factors were not significant.

In recent years, the effects of both plant spacing variability and plant emergence variability have received considerable attention from corn producers and agronomists as they strive to maximize grain yield. A stand of commercially grown corn at first glance may appear to be uniform, but on closer inspection it often becomes apparent that within-row corn stands are not uniform. There may be crowded plants (doubles and clusters), long or short gaps, and their combinations. Such spacing irregularities are often related to the ability of the planter to singulate seeds and to uniformly transfer seeds from the singulating mechanism down into the seed furrow. In addition to spacing variability, a corn stand may also emerge nonuniformly. Variation in planting depth, cold soils, and poor seed-to-soil contact may cause variation in plant emergence and development. Various studies have been conducted to examine corn yield response to each of these types of stand variation.

Conclusions regarding the effect of spacing variability on corn yield have been mixed. Nielsen (2001) reported that corn grain yield decreased an average of 62 kg ha^{-1} for every centimeter increase in plant spacing standard deviation above 5 cm. Krall et al. (1977) reported an 84 kg ha^{-1} yield reduction for each centimeter increase in standard deviation, and also speculated that a curvilinear relationship existed between grain yield and the standard deviation of spacing between consecutive plants in the row. Vanderlip et al. (1988) found that grain yield was increased by increasing precision of plant spacing. Other studies, however, suggest that nonuniform plant spacing does not reduce grain yield. Erbach et al. (1972) compared yield of individual plants, which differed in distance from adjacent plants in the row, and concluded that no significant yield benefit could be obtained with more uniform plant spacing than that normally produced by properly adjusted conventional planters. Muldoon and Daynard (1981) indicated that yield was unaffected by the presence of gaps up to 1 m long within the row. Similarly, Edmeades and Daynard (1979), Daynard and Muldoon (1983), Lauer (2001), and Liu et al. (2004) found no significant improvement in grain yields with reduced plant spacing variability.

Conclusions of studies examining the effect of emergence variability have been more consistent. A growth stage difference of two leaves or greater between adjacent plants results in the younger plant being barren at the end of the season (Nielsen, 2001). Uniform plant height, which is an indication of uniform emergence, is associated with higher yields (Glenn and Daynard, 1974). Nafziger et al. (1991) indicated that plant emergence variability impacts on potential yield even if within-row plant spacing is relatively uniform. If the difference in emergence times of plants in an unevenly emerged field is <2 wk, yield loss will likely occur; however, this loss will probably not be large enough to justify replanting. If emergence delays for some plants approach 3 wk, then replanting may produce yield increases of about 10% if the proportion of delayed plants exceeds 25%. Other studies also reported significant yield reductions due to uneven seedling emergence of corn plants (Nafziger et al., 1991; Ford and Hicks, 1992). Late-emerging plants within a row must compete for incident solar radiation, moisture, and nutrients with earlier-emerging neighboring plants which are often taller and have a more developed root system. If compe-

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Abbreviations: CHU, crop heat unit; LAI, leaf area index.

tition is severe, late-emerging plants may not produce grain and may actually function as weeds in the canopy.

Nonuniform plant spacing does not consistently reduce corn grain yield, unlike nonuniform emergence. The mechanisms allowing a corn canopy to compensate for variations in spacing while not compensating for variations in emergence have not been studied. Furthermore, it is not clear whether there exists an interaction between emergence and spacing variability, and whether inconsistencies in response to spacing variability may be associated with emergence patterns. The objective of this study was (i) to quantify the effects and interactions of plant spacing variability and plant emergence variability on growth and grain yield of corn, and (ii) to determine how the growth and grain yield of individual corn plants within a canopy are affected by variations in emergence timing or spacing.

MATERIALS AND METHODS

Field experiments were conducted in 2000 and 2001 at the Elora Research Station (43°39′ N, 80°25′ W, elevation 376 m) and the Woodstock Research Station (43°08′ N, 79°06′ W, elevation 317 m) in southcentral Ontario, Canada. The growing season is rated as receiving 2650 Crop Heat Units (CHU; Brown and Bootsma, 1993) at Elora and 2850 CHU at Woodstock. At Elora, the loam soil is an imperfectly drained medium, mixed, weakly to moderately calcareous Typic Hapludalf with tile drainage and an organic matter content of 3.8 to 4.0%. The loam soil at Woodstock is a well-drained medium, mixed, alkaline, moderately to very strongly calcareous Typic Hapludalf with 2 to 3% organic matter. Fall moldboard plowing followed by one or two spring cultivations was conducted before planting in both locations and both years. The previous crop was alfalfa (*Medicago sativa* L.) at Elora and soybean [*Glycine max* (L.) Merr.] at Woodstock. Starter fertilizer was applied through the planter at a rate of 20 kg N ha^{-1}, 80 kg P_2O_5 ha^{-1}, and 40 kg K_2O ha^{-1}. Additional N was injected between rows at about 4 to 5 wk after planting, as urea-NH_4NO_3 at a rate of 150 kg N ha^{-1}. Glyphosate [*N*-(phosphonomethy)glycine] was sprayed 5 to 6 wk after planting at a rate of 3.5 L ha^{-1} for weed control. Roundup Ready (Monsanto Co., St. Louis, MO) corn hybrids DK335 and DK C42-21RR were planted at Elora and Woodstock, respectively.

In each experiment, plots were 23-m long and consisted of four 0.76-m rows. Three of the four rows were machine planted with a vacuum planter (John Deere 1750, Moline, Illinois). One of the two center rows was hand planted to achieve the treatments described below. Each hand-planted row consisted of 19 repeated sequences of six-plant units. Both hand- and machine-planted rows were arranged at the target plant population of 67 000 plants ha^{-1}.

Nine treatments were arranged in a 3 by 3 factorial experiment (Fig. 1) and replicated four times in a randomized complete block design. The first factor was emergence delay. A zero-leaf delay (E), a two-leaf delay (EM), and a four-leaf delay (EL) in emergence was established for one of the six plants in each unit. The position number of each plant in the repeatable six-plant unit was marked as No. 1, No. 2, No. 3, No. 4, No. 5, and No. 6 (Fig. 1). The plant in position No. 3 was the only plant that had a delay in emergence timing. Emergence delays of two leaves were achieved by delaying planting date until previously planted corn had emerged. This method was based on previous research findings that indicated that thermal time required for corn emergence is approximately equivalent to the thermal time accumulated between the appearance of two consecutive leaves. Corn emergence dates were delayed by 8 to 16 d (average 12 d) and by 15 to 25 d (average 21 d) for the emergence treatment of two-leaf stage delay and four-leaf stage delay, respectively (Table 1). Although the calendar days of delay varied among locations and years, the thermal time (Tollenaar et al., 1979) of a two-leaf stage delay (EM) and four-leaf stage delay (EL) were achieved at all locations in both years. The thermal time required for emergence ranged from 152-165 CHU (Table 1).

The second factor was within-row plant spacing variability (Fig. 1). The three plant spacing treatments were uniform plant spacing (20 cm), one short-gap (40 cm) associated with a double in each six-plant unit, and one long-gap (60 cm) associated with a triple in each six-plant unit. The doubles and triples were planted side by side within 3 cm in the row. In theory, the standard deviation of plant spacing for each of the three spacing treatments indicated in Fig. 1 should be 0, 12.0, and 20.8 cm. However, actual values were measured as 2.5, 10.0, and 17.5 cm, respectively. Differences between theoretical and actual values of the standard deviation were caused by experimental error associated with seed placement, measurement, as well as slight deviations in emergence location relative to seed placement location.

The number of days required to achieve 50% corn emergence was recorded by counting plant populations daily, until 100% emergence, in the entire hand-planted row in each plot. Within-row plant-to-plant spacing was measured with a Space Cadet plant stand analyzer (Version 1.9, Bagley, Iowa) in the hand-planted row 2 wk after silking. In a previous study (Liu et al., 2004), results found with this device were compared with manual measurement of spacing and were confirmed to be accurate. At 2 wk postsilking of the early planting, plant height from ground to the tip of tassel was measured for five six-plant units (30 plants total) in each plot. Plant samples were taken at 5 wk after the early-plant emergence and 2 wk after the early-plant silking. At each sampling date, the aboveground biomass of 12 consecutive plants in two six-plant units was harvested from a premarked sampling area. Green leaf area of all harvested plants was measured with a LI-3000 leaf area meter (LI-COR, Lincoln, Nebraska). The leaves and stems of sample plants were dried at 80°C for 72 h before measurement of plant dry matter. At maturity, aboveground dry matter and grain was measured for five six-plant units in every plot. Grain yields were adjusted to 155 g kg^{-1} moisture. The numbers of plants that had barren ears (i.e., no grain per plant) were recorded at this time. Harvest index was determined by calculating the ratio of grain dry weight and total aboveground dry matter. All measurements were done by plant positions and the data for each plant were kept separate for analysis.

Crop heat unit accumulation was calculated from data that were collected daily by weather stations located near the experimental sites. The CHU was calculated by summing the daily CHU accumulated to that day. The following formulas were used for calculating the daily CHU (Tollenaar et al., 1979):

$$\text{Daily CHU} = [\text{CHU(day)} + \text{CHU(night)}]/2$$

$$\text{CHU(day)} = 3.33 \times (T_{\max} - 10°\text{C}) - 0.084 \times (T_{\max} - 10°\text{C})^2$$

$$\text{CHU(night)} = 9/5\ (T_{\min} - 4.4),$$

where $T_{\max}$ and $T_{\min}$ are the maximum and minimum temperature for the 24-h interval.

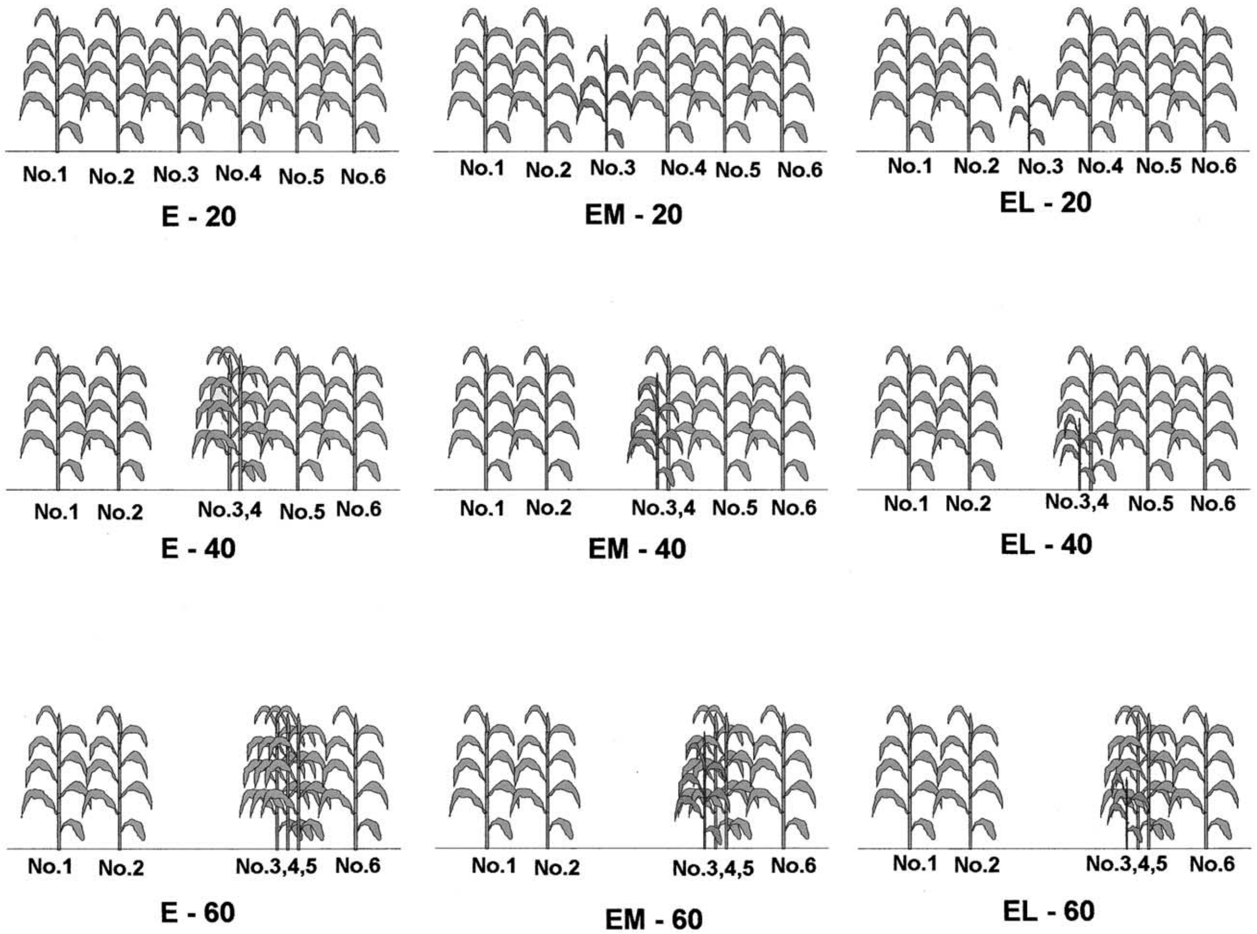

Fig. 1. Plant spacing and emergence treatments are composed of repeatable sequences and each sequence unit consists of six corn plants: E, early emergence; EM, early emergence except for one plant with a two-leaf emergence delay; EL, early emergence except for one plant with a four-leaf emergence delay; 20, corn plants spaced uniformly at 20 cm; 40, corn plants spaced uniformly at 20 cm except for one 40-cm gap and double plants; 60, corn plants spaced uniformly at 20 cm except for one gap of 60-cm spacing and triple plants. The numbers under diagram indicate plant position.

Statistical Analyses

Within-row plant spacing variability was determined by calculating the plant spacing standard deviation. Every plant position in each six-plant unit was unique in terms of interplant competition and was considered as a treatment. For example, plant No. 1 in unit E-20 was a treatment, and this treatment was equivalent to other No. 1 plants in all units (Fig. 1). Therefore, the analysis was performed on the basis of 54 unique plant positions. Since all six plants in the unit E-20 were uniformly spaced and emerged, the averaged value of each measured character was treated as a control. Analyses of variance were performed for the same plant positions in each unit that had the variation in emergence and plant spacing with the PROC GLM procedure of SAS (version 6.12, SAS Institute, Cary, NC). A protected LSD was used to compare means of the same plant position in all units, and selected orthogonal single degree of freedom contrasts were computed. Unless indicated, effects were considered significant in all statistical calculations if $P \leq 0.05$.

RESULTS AND DISCUSSION

Precipitation at both locations varied dramatically across the two growing seasons (Table 2). Above-average levels were received in 2000 and below-average levels in 2001, particularly during June, July, and August. Despite large differences in precipitation across the two growing seasons, corn growth and yield responded similarly to plant emergence variability and plant spacing variability across years. Interactions between treatments and location and between treatments and year were generally not significant, and therefore only means across locations and years will be discussed.

Grain Yield

Grain yield was reduced by plant emergence variability but not by plant spacing variability. Averaged across plant position and the three plant spacing treatments, corn yielded 4% (0.33 Mg ha^{-1}) and 8% (0.70 Mg ha^{-1}) less when one out of six plants had a delay in emergence of two leaf stages (12 d) and four leaf stages (21 d), respectively (Table 3). Averaged across plant position and the three emergence treatments, the treatments of uniform spacing, a short-gap associated with a double, and a long-gap associated with a triple produced a grain yield of 8.16, 8.08, and 8.02 Mg ha^{-1}, respectively ($P = 0.6092$) (Table 3). There was no interaction between emergence and spacing treatments for grain yield. The

Table 1. Dates and number of days of corn planting and emergence for the early (E), medium (M), and late (L) emergence treatments, and crop heat unit (CHU) accumulations for the interval from planting date (PD) to emergence date (ED) of corn grown at Elora and Woodstock, ON, Canada, in 2000 and 2001.

				PD − ED	
Location	Year	PD	ED	d	CHU†
Elora	2000	05 May	15 May (E)	10	159
		15 May	31 May (M)	16	165
		31 May	09 June (L)	9	160
	2001	09 May	20 May (E)	11	163
		20 May	03 June (M)	14	154
		03 June	12 June (L)	9	163
Woodstock	2000	15 May	28 May (E)	13	154
		28 May	05 June (M)	8	152
		05 June	12 June (L)	7	154
	2001	01 May	10 May (E)	9	164
		10 May	20 May (M)	10	160
		20 May	02 June (L)	13	156

† CHU was calculated with the formula developed by Brown and Bootsma (1993). The base temperature for the day and the night is 10 and 4.4°C, respectively. Cumulative CHU was calculated by summing the daily CHU accumulated to that date.

overall response was similar to that reported by Ford and Hicks (1992). This result is consistent with the contention that there is no significant relationship between grain yield and within-row plant spacing variability (Erbach et al., 1972; Muldoon and Daynard, 1981; Lauer, 2001; Liu et al., 2004).

Per-plant yield reductions observed with crowded plants were offset by per-plant yield increases of other plants in the six-plant unit. For treatments E-40 and E-60, plants situated in double or triple stands produced 7 to 11% less grain yield than the control (Table 3). Conversely, plant No. 2, directly next to the gap, had significantly higher per-plant yields. The yield of plant No. 2 next to a 40-cm gap consistently yielded an average of 9% more grain than the control, and this plant next to a 60-cm gap attained a 10 to 19% yield increase over the control. Similarly, grain yield of plant No. 1, the second plant from the gap, increased when a 60-cm gap occurred.

Per-plant yield reductions of late-emerging plants were only partially offset by per-plant yield increases of neighboring plants. For treatments EM-20 and EL-20, per-plant yields No. 2 and 4 that were next to late-emerging plants increased by 2 to 7%, but this was not sufficient to compensate for the 35 to 72% yield decrease of the late emerging plant. Late-emerging plants always produced low per-plant yields (Table 3). Grain yield of plant No. 3 was decreased by about 40 g plant^{-1} or 36% for every two-leaf stage delay in emergence.

Table 2. Monthly precipitation and mean air temperature for two growing seasons and the 30-yr average at Elora and Woodstock, ON, Canada, in 2000 and 2001.

		Month					
Location	Year	May	June	July	August	September	Five-month total or mean
		Precipitation, mm					
Elora	2000	123	162	108	51	47	490
	2001	110	45	41	72	74	341
30-yr average		78	87	73	76	74	388
Woodstock	2000	103	172	153	61	89	578
	2001	101	39	14	46	65	264
30-yr average		70	78	80	70	74	372
		Mean air temperature, °C					
Elora	2000	13	18	18	18	12	16
	2001	13	18	19	20	14	17
30-yr average		11	17	19	15	13	15
Woodstock	2000	14	19	18	19	13	17
	2001	14	19	20	20	14	17
30-yr average		12	18	20	19	15	17

Table 3. Effect of plant spacing and emergence on relative grain yield per plant of corn at different plant positions within a row. Values represent means across two locations (Elora and Woodstock, ON, Canada) and 2 yr (2000 and 2001).

	Plant position‡						
Treatment†	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	Mean
	Relative yield, %§						
E-20(Control)	100	100	100	100	100	100	100
E-40	101	110**	93	90*	99	100	99
E-60	103	110**	94	89**	89**	100	98
EM-20	100	103	65**	102	99	102	95
EM-40	102	108*	56**	101	105	100	95
EM-60	105	114**	53**	94	97	100	94*
EL-20	101	107	28**	106	102	102	91**
EL-40	102	109*	16**	104	106	103	90**
EL-60	107	119**	16**	95	103	103	90**
LSD ($P < 0.05$)	NS¶	7	7	8	8	NS	5
Contrasts							
E vs. (EM + EL)/2	NS	NS	**	**	**	NS	**
EM vs. EL	NS	NS	**	NS	NS	NS	*
20 vs. (40 + 60)/2	NS	**	**	**	NS	NS	NS
40 vs. 60	NS	*	NS	*	**	NS	NS

* Significantly different from the control at $P = 0.05$.

** Significantly different from the control at $P = 0.01$.

† E, early emergence; EM, early emergence except for one plant with a two-leaf emergence delay; EL, early emergence except for one plant with a four-leaf emergence delay; 20, corn plants spaced uniformly at 20 cm; 40, corn plants spaced uniformly at 20 cm except for one 40-cm gap and double plants; 60, corn plants spaced uniformly at 20 cm except for one gap of 60-cm spacing and triple plants.

‡ Plant position in a six-plant sequence with varied spacing and emergence (see Fig. 1).

§ Grain yield of any plant position treatment compared with the control (112.6 g plant^{-1}).

¶ NS = not significant at $P = 0.05$.

In stands that included a combination of uneven emergence and nonuniform plant spacing, yield compensation was greater than in the stands where only spacing or emergence variation occurred. For instance, per-plant yield reductions for plant No. 3 in EM-40 was 44% (49.6 g) vs. 7% for plant No. 3 in E-40. However in EM-40, per-plant yield increases were observed for plant No. 1, 2, 4, and 5. Yield compensation by these plants ranged from 1 to 8% and totaled 15.5 g. Consequently, mean grain yield for EM-40 relative to E-20 was only decreased by 5%. Similar trends were observed in EL-60 where compensatory yield increases of 3 to 19% were observed for plants No. 1, 2, 5, and 6.

Plant No. 3 with a four-leaf stage emergence delay in the uniformly spaced treatment (EL-20) produced 28% grain yield compared with the control, while this plant in a double or triple stand (EL-40 and EL-60) produced only 16% yield of the control. Although yield decreases appeared to be greater when the late emerging plant was part of a double or triple stand, the interaction between spacing and emergence treatments was not significant in a six plant unit.

Plant Height

Per-plant yield reductions observed for late-emerging plants were associated with height reductions. Whereas

Table 4. Effect of plant spacing and emergence on plant height of corn at 2 wk after silking at different plant positions within a row. Values represent means across two locations (Elora and Woodstock, ON, Canada) and 2 yr (2000 and 2001). See Fig. 1 for the treatment symbols.

	Plant position‡						
Treatment†	**No. 1**	**No. 2**	**No. 3**	**No. 4**	**No. 5**	**No. 6**	**Mean**
				cm			
E-20(Control)	250	250	250	250	250	250	250
E-40	247	248	240	246	249	244	246
E-60	250	250	247	246	246	251	248
EM-20	253	253	245	247	245	247	248
EM-40	249	251	229**	248	247	249	246
EM-60	250	251	230**	248	251	248	246
EL-20	242	244	206**	247	243	244	237**
EL-40	250	251	186**	250	248	251	239**
EL-60	250	249	190**	250	252	252	240**
LSD ($P < 0.05$)	NS§	NS	17	NS	NS	NS	7
Contrasts							
E vs. (EM + EL)/2	NS	NS	**	NS	NS	NS	*
EM vs. EL	NS	NS	**	NS	NS	NS	NS
20 vs. (40 + 60)/2	NS	NS	**	NS	NS	NS	NS
40 vs. 60	NS	NS	NS	NS	NS	NS	NS

* Significantly different from the control at $P = 0.05$.

** Significantly different from the control at $P = 0.01$.

† E, early emergence; EM, early emergence except for one plant with a two-leaf emergence delay; EL, early emergence except for one plant with a four-leaf emergence delay; 20, corn plants spaced uniformly at 20 cm; 40, corn plants spaced uniformly at 20 cm except for one 40-cm gap and double plants; 60, corn plants spaced uniformly at 20 cm except for one gap of 60-cm spacing and triple plants.

‡ Plant position in a six-plant sequence with varied spacing and emergence (see Fig. 1).

§ NS = not significant at $P = 0.05$.

plant spacing had no effect on plant height, emergence delays consistently resulted in decreases in maximum plant height (Table 4). Height of plant No. 3, averaged across three plant spacing treatments at 2 wk after silking was 246, 235, and 194 cm for a zero-, two-, and four-leaf delay in emergence, respectively. Mean final plant height of each six-plant unit did not differ between treatments of no delayed emergence and two-leaf stage delay, but differed significantly between no delayed emergence and four-leaf stage delay. These results suggest that corn plant height is not reduced if plant emergence delay is less than two-leaf stages. Late-emerging plants do not grow as tall as earlier-emerging plants if plant emergence is delayed by four-leaf stages or more. In competition studies, height advantage has been shown to be strongly correlated with ability to intercept radiation and biomass production. Height reductions of late-emerging plants may have resulted from the combined effect of limitations in dry matter available for stem elongation, and by the shortening of phenological stages during which node production occurs. Averaged across spacing treatments, plants with an emergence delay of 0, 2, and 4 leaves had final leaf numbers of 18.0, 17.5, and 17.0, respectively. There was no interaction between emergence date and spacing.

Leaf Area

Yield compensation mechanisms can also be explained by leaf area characteristics of the various treatments. At 5 wk after emergence, individual plants in double or triple stands that emerged uniformly (e.g., plant No. 3 in E-40, and No. 3 and 4 in E-60), had smaller leaf areas than plants that were uniformly spaced (Table 5). Mean leaf area of E-40 and E-60, however, was not affected by spacing variation, indicating that plants No. 1, 2, 5, and 6 were able to compensate with increased leaf area. At 2 wk after silking, per-plant leaf area did not differ by plant position for the three spacing treatments. This observation regarding spacing was generally consistent across uniformly and nonuniformly emerging treatments as indicated by the orthogonal contrasts comparing 20 vs. (40 + 60)/2 (Table 5).

Yield reductions associated with treatments having late-emerging plants are consistent with reductions in leaf area. Corn plants that emerged two or four leaves late consistently had lower leaf areas (Table 5). Averaged across three plant spacing treatments, plant No. 3, when delayed by 2- and 4-leaf stages, had 18 and 40%, respectively, lower leaf area than the control plants at 2 wk after silking. Leaf area of late emerging plants was reduced more when associated with a double or triple stand. As indicated by the orthogonal contrast comparing E vs. (EM + EL)/2, delayed emergence of one plant in the six-plant unit had a negative effect on mean leaf area and plants adjacent to the late emerging plant did not compensate with increased leaf area.

Dry Matter Accumulation

Response of dry matter accumulation to plant emergence variability and spacing variability was similar to the response of LAI and yield (Table 6). While individual plant dry matter was affected by spacing variability, mean dry matter averaged across emergence treatments was not affected (Table 6). Plants close to a gap produced significantly more dry matter and were able to offset reductions experienced by plants in double or triple stands. This result is consistent across emergence timings [orthogonal contrast 20 vs. (40 + 60)/2, Table 6].

In the EM and EL treatments, plant No. 3 had less dry matter accumulation at 5 wk after emergence and at 2 wk after silking. The reduction in dry matter accumulation at 2 wk after silking was 42 and 72% for two-leaf stage delay and four-leaf stage delay, respectively. Dry matter reductions due to emergence delays were accentuated when the late emerging plant emerged in a double or triple stand. Plants neighboring a late-emerging plant (i.e., plant No. 1, 2, 4, and 5) did not have significant increases in dry matter compared with the control [see orthogonal contrast E vs. (EM + EL)/2, Table 6]. Consequently, the mean dry matter accumulation for treatments with late-emerging plants was significantly less than treatments that emerged uniformly.

Net assimilation rate (NAR) indicates the dry matter accumulation rate per unit of leaf area (Brown, 1984). In this study, the highest NAR of 7.3 g m^{-2} d^{-1} was measured for the early emergence treatment during the period from 5 wk after emergence to 2 wk postsilking. When averaged across three plant spacing treatments, NAR was 10% lower for a two-leaf stage delay and 17% lower for a four-leaf stage delay compared with the uniformly early emergence treatment. Dry matter

Table 5. Effect of plant spacing and emergence on leaf area per plant of corn at different plant positions within a row. Values at both sampling dates represent means across two locations (Elora and Woodstock, ON, Canada) and 2 yr (2000 and 2001).

	Plant position‡						
Treatment†	**No. 1**	**No. 2**	**No. 3**	**No. 4**	**No. 5**	**No. 6**	**Mean**
	cm^2 $plant^{-1}$						
5 wk after emergence of early planted corn							
E-20(Control)	789	789	789	789	789	789	789
E-40	720	767	679*	730	724	694	719
E-60	803	756	687*	634*	685	767	722
EM-20	780	835	320**	768	790	750	707*
EM-40	740	766	283**	655	781	744	662**
EM-60	800	847	278**	644*	679*	832	680*
EL-20	759	740	164**	830	814	731	673*
EL-40	728	858	144**	801	819	749	683*
EL-60	787	788	106**	597**	631*	718	605**
LSD ($P < .05$)	NS§	NS	111	142	147	NS	101
Contrasts							
E vs. (EM+EL)/2	NS	NS	**	NS	NS	NS	**
EM vs. EL	NS	NS	**	NS	NS	NS	NS
20 vs. (40+60)/2	NS	NS	*	**	*	NS	NS
40 vs. 60	NS	NS	NS	*	*	NS	NS
2 wk after silking of early planted corn							
E-20(Control)	4170	4170	4170	4170	4170	4170	4170
E-40	4350	4420	4330	4200	4240	4230	4300
E-60	4200	4470	4130	3920	4280	4230	4210
EM-20	4360	4470	3610**	4380	4160	4430	4230
EM-40	4160	4370	3470**	4150	4270	4310	4120
EM-60	4430	4480	3200**	3980	4270	4270	4100
EL-20	4440	4240	2670**	4130	4240	4140	3980
EL-40	4300	4530	2410**	4330	4120	4390	4010
EL-60	4210	4480	2400**	4050	4290	4110	3920
LSD ($P < 0.05$)	NS	NS	321	NS	NS	NS	NS
Contrasts							
E vs. (EM + EL)/2	NS	NS	**	NS	NS	NS	*
EM vs. EL	NS	NS	**	NS	NS	NS	*
20 vs. (40 + 60)/2	NS	NS	NS	NS	NS	NS	NS
40 vs. 60	NS	NS	NS	*	NS	NS	NS

* Significantly different from the control at $P = 0.05$.

** Significantly different from the control at $P = 0.01$.

† E, early emergence; EM, early emergence except for one plant with a two-leaf emergence delay; EL, early emergence except for one plant with a four-leaf emergence delay; 20, corn plants spaced uniformly at 20 cm; 40, corn plants spaced uniformly at 20 cm except for one 40-cm gap and double plants; 60, corn plants spaced uniformly at 20 cm except for one gap of 60-cm spacing and triple plants.

‡ Plant position in a six-plant sequence with varied spacing and emergence (see Fig. 1).

§ NS = not significant at $P = 0.05$.

accumulation was significantly correlated with leaf area at 5 wk after emergence ($r = 0.99$) and at 2 wk postsilking ($r = 0.95$). Crop dry matter accumulation is a good predictor of the interception of incident solar radiation, which is related to leaf area (Tollenaar, 1983). Hence, results indicate that the difference in dry matter accumulation due to emergence and within-row plant spacing variability is associated with seasonal interception of incident solar radiation.

Leaf-to-Stem Ratio

Dry matter partitioning was affected by spacing and emergence variability. Plants that had delayed emergence or emerged in a double or triple stand were observed to have long and narrow leaves with short and thin stems. At 2 wk after silking, the two highest leaf dry wt. to stem dry wt. ratios were found in the plants with a combination of four-leaf emergence delay and double or triple stands (Table 7, plant No. 3). In general, the leaf-to-stem ratio was lower for the plants next to a gap (plant No. 2 with 60-cm spacing) and higher for the plants in double or triple (plant No. 4 with 40- and 60-cm spacing) compared with uniform plant spacing.

Harvest Index

Harvest index was stable from 0.49 to 0.51 for all plant positions except for the late-emerging plants (Table 8). Averaged across plant spacing treatments, the harvest index of plant No. 3 was reduced by 15% for a two-leaf stage delay and by 53% for a four-leaf stage delay. There was a significant interaction for spacing and emergence delay ($P = 0.0020$). Reductions in harvest index were intensified when delayed emergence plants were grown in double or triple stands. The mean harvest index of each six-plant unit was also affected by delayed emergence.

Differences in harvest index were related to the incidence of ear barrenness for emergence treatments in 2001 at both locations (data not shown). This impact was probably related to the drought stress experienced from late June to early September in 2001 (Table 2). Barrenness was <0.5, but increased to 2.5, and to 6.0% for E, EM, and EL treatments, respectively. No emergence × spacing interactions were observed, indicating that the percentage of ear barrenness was consistent among the three plant spacing treatments.

CONCLUSIONS

Corn is more responsive to plant emergence variability than plant spacing variability. There were no mean-

Table 6. Effect of plant spacing and emergence on dry matter accumulation of corn at different plant positions within a row. Values at both sampling dates represent means across two locations (Elora and Woodstock, ON, Canada) and 2 yr (2000 and 2001).

	Plant position‡						
Treatment†	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	Mean
	g plant^{-1}						
5 wk after emergence of early planted corn							
E-20(Control)	6.3	6.3	6.3	6.3	6.3	6.3	6.3
E-40	5.7	6.1	5.3*	5.7	5.8	5.4	5.7
E-60	6.3	6.2	5.3*	4.6*	5.2*	6.1	5.6
EM-20	6.2	6.7	2.2**	6.1	6.3	5.9	5.6
EM-40	5.8	6.1	1.7**	5.1	6.3	6.1	5.2*
EM-60	6.2	7.3	1.5**	4.9*	5.0*	6.7	5.3*
EL-20	6.0	6.1	0.9**	6.2	6.3	5.8	5.2*
EL-40	5.6	6.9	0.9**	6.2	6.4	5.9	5.3*
EL-60	6.1	6.1	0.5**	4.6*	5.0*	5.7	4.7**
LSD ($P < 0.05$)	NS§	NS	0.9	1.2	1.1	NS	1.0
Contrasts							
E vs. (EM+EL)/2	NS	NS	**	NS	NS	NS	*
EM vs. EL	NS	NS	**	NS	NS	NS	NS
20 vs. (40+60)/2	NS	NS	*	**	*	NS	NS
40 vs. 60	NS	NS	NS	*	**	NS	NS
2 wk after silking of early planted corn							
E-20(Control)	121	121	121	121	121	121	121
E-40	123	138**	112	113	121	120	121
E-60	123	138**	114	100**	119	115	118
EM-20	126	130	72**	130	115	136	118
EM-40	121	135*	67**	108	122	123	113
EM-60	131	137*	62**	98**	118	120	111*
EL-20	131	129	40**	123	121	121	111*
EL-40	122	139**	29**	119	122	130	110*
EL-60	124	137*	28**	115	120	119	107**
LSD ($P < 0.05$)	NS	14.2	10.3	15.2	NS	NS	9.4
Contrasts							
E vs. (EM + EL)/2	NS	NS	**	NS	NS	NS	**
EM vs. EL	NS	NS	**	NS	NS	NS	NS
20 vs. (40 + 60)/2	NS	**	**	**	NS	NS	NS
40 vs. 60	NS	NS	NS	*	NS	NS	NS

* Significantly different from the control at $P = 0.05$.

** Significantly different from the control at $P = 0.01$.

† E, early emergence; EM, early emergence except for one plant with a two-leaf emergence delay; EL, early emergence except for one plant with a four-leaf emergence delay; 20, corn plants spaced uniformly at 20 cm; 40, corn plants spaced uniformly at 20 cm except for one 40-cm gap and double plants; 60, corn plants spaced uniformly at 20 cm except for one gap of 60-cm spacing and triple plants.

‡ Plant position in a six-plant sequence with varied spacing and emergence (see Fig. 1).

§ NS = not significant at $P = 0.05$.

Table 7. Effect of plant spacing and emergence on leaf-to-stem ratio of corn in 2 wk postsilking at different plant positions within a row. Values represent means across two locations (Elora and Woodstock, ON, Canada) and 2 yr (2000 and 2001).

	Leaf-to-stem ratio‡						
	Plant position§						
Treatment†	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	Mean
E-20(Control)	0.32	0.32	0.32	0.32	0.32	0.32	0.32
E-40	0.31	0.30	0.34	0.33	0.30	0.32	0.32
E-60	0.31	0.30	0.35	0.34	0.31	0.33	0.32
EM-20	0.31	0.31	0.44**	0.32	0.31	0.31	0.34**
EM-40	0.31	0.31	0.44**	0.34	0.32	0.31	0.34**
EM-60	0.32	0.31	0.43**	0.34	0.32	0.33	0.34**
EL-20	0.31	0.30	0.59**	0.31	0.31	0.31	0.36**
EL-40	0.31	0.30	0.65**	0.33	0.30	0.31	0.37**
EL-60	0.30	0.29*	0.64**	0.33	0.32	0.32	0.37**
LSD ($P < 0.05$)	NS¶	0.03	0.05	NS	NS	NS	0.02
Contrasts							
E vs. (EM+EL)/2	NS	NS	**	NS	NS	NS	**
EM vs. EL	NS	NS	**	NS	NS	NS	**
20 vs. (40+60)/2	NS	*	NS	**	NS	NS	NS
40 vs. 60	NS	NS	NS	NS	NS	NS	NS

* Significantly different from the control at $P = 0.05$.

** Significantly different from the control at $P = 0.01$.

† E, early emergence; EM, early emergence except for one plant with a two-leaf emergence delay; EL, early emergence except for one plant with a four-leaf emergence delay; 20, corn plants spaced uniformly at 20 cm; 40, corn plants spaced uniformly at 20 cm except for one 40-cm gap and double plants; 60, corn plants spaced uniformly at 20 cm except for one gap of 60-cm spacing and triple plants.

‡ Dry weight ratio of leaf (blade) and stem (including sheaths).

§ Plant position in a six-plant sequence with varied spacing and emergence (see Fig. 1).

¶ NS = not significant at $P = 0.05$.

Table 8. Effect of plant spacing and emergence on harvest index of corn at different plant positions within a row. Values represent means across two locations (Elora and Woodstock, ON, Canada) and 2 yr (2000 and 2001).

	Plant position‡						
Treatment†	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	Mean
	kg kg^{-1}						
E-20(Control)	0.50	0.50	0.50	0.50	0.50	0.50	0.50
E-40	0.51	0.51	0.50	0.49	0.50	0.51	0.50
E-60	0.50	0.50	0.50	0.49	0.50	0.50	0.50
EM-20	0.50	0.50	0.45**	0.49	0.50	0.50	0.49*
EM-40	0.50	0.50	0.42**	0.50	0.51	0.50	0.49*
EM-60	0.50	0.51	0.41**	0.51	0.51	0.50	0.49*
EL-20	0.50	0.51	0.29**	0.50	0.51	0.51	0.47**
EL-40	0.49	0.50	0.20**	0.50	0.51	0.50	0.45**
EL-60	0.51	0.50	0.21**	0.50	0.50	0.50	0.45**
LSD ($P < 0.05$)	NS§	NS	0.03	NS	NS	NS	0.01
Contrasts							
E vs. (EM + EL)/2	NS	NS	**	NS	NS	NS	**
EM vs. EL	NS	NS	**	NS	NS	NS	**
20 vs. (40 + 60)/2	NS	NS	**	NS	NS	NS	*
40 vs. 60	NS	NS	NS	NS	NS	NS	NS

* Significantly different from the control at $P = 0.05$.

** Significantly different from the control at $P = 0.01$.

† E, early emergence; EM, early emergence except for one plant with a two-leaf emergence delay; EL, early emergence except for one plant with a four-leaf emergence delay; 20, corn plants spaced uniformly at 20 cm; 40, corn plants spaced uniformly at 20 cm except for one 40-cm gap and double plants; 60, corn plants spaced uniformly at 20 cm except for one gap of 60-cm spacing and triple plants.

‡ Plant position in a six-plant sequence with varied spacing and emergence (see Fig. 1).

§ NS = not significant at $P = 0.05$.

ingful significant interactions between within-row plant spacing variability and plant emergence variability for all measured plant performances in this study, including grain yield. The data from this study suggest that a moderate level of plant spacing variability (standard deviation from 2.5 to 17.5 cm) does not cause severe interplant competition, even in stands with delayed emergence. In stands of nonuniform plant spacing and uneven plant emergence, the yield decrease was largely determined by uneven plant emergence. In double or triple stands spaced in 0 to 3 cm apart, this reduction was 6 to 10% compared with the uniformly spaced stands. This effect was most likely attributable to competition for light at an early stage of development with an indication of the higher plant height, lower leaf area, and less dry matter accumulation in double and triple stands. However, if the nonuniform plant spacing occurred under the same plant population in a field, the reduced yield could largely be compensated by the plants near or close to the gaps. As a result, the total yield decrease was often not significant.

Delayed emergence resulted in less leaf area and dry matter accumulations, high leaf-to-stem ratios, low harvest index, and consequently, those late-emerging plants produced less grain yield than the uniformly emerged plants. In both uniformly and nonuniformly spaced stands, yields of plants with a two-leaf or four-leaf stage delay in emergence were decreased by 35 to 47% or 72 to 84%, respectively. This yield decline was never offset by increased yield of its neighbors and always caused a significant total yield decrease in each six-plant unit, regardless of the spacing differences. In this study, the uneven emerging stands yielded less primarily because of the slower rate of plant development in late-emerging plants and the direct competition from their older and larger neighbors. Interactions between within-row plant spacing variability and plant emergence variability on grain yield were significant at the plant level, but not at the canopy level. Reductions in grain yield were attributable to both a reduction in harvest index and a reduction in dry matter accumulation.

Results of this study indicate that nonuniform plant spacing within the row has little or no effect on plant growth and grain yield of corn if the plant population is adequate for high yield. Uneven seedling emergence, however, almost always affects plant growth and reduces grain yield, with earlier emerged plants unable to compensate for lower yield of late-emerging plants. In addition, the yield of an individual plant is influenced not only by the directly adjacent plants but also by a second adjacent plant. Finally, our results indicate that yield reduction due to variation in plant emergence and within-row plant spacing are both directly and indirectly (i.e., harvest index) the result of a reduction in dry matter accumulation, which in turn is associated with a reduction in leaf area per plant.

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