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Plant-to-Plant Variability in Corn Production

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ABSTRACT

Corn (*Zea mays* L.) grain yields are known to vary from plant to plant, but the extent of this variability across a range of environments has not been evaluated. This study was initiated to evaluate by-plant corn grain yield variability over a range of production environments and to establish the relationships among mean grain yield, standard deviation, coefficient of variation, and yield range. A total of forty-six 8- to 30-m corn transects were harvested by plant in Argentina, Mexico, Iowa, Nebraska, Ohio, Virginia, and Oklahoma from 2002 to 2004. By-plant corn grain yields were determined, and the average individual plant yields were calculated. Over all sites in all countries and states, plant-to-plant variation in corn grain yield averaged 2765 kg ha^{-1} (44.1 bu ac^{-1}). At the sites with the highest average corn grain yield (11 478 and 14 383 kg ha^{-1}, Parana Argentina, and Phillips, NE), average plant-to-plant variation in yield was 4211 kg ha^{-1} (67 bu ac^{-1}) and 2926 kg ha^{-1} (47 bu ac^{-1}), respectively. As average grain yields increased, so did the standard deviation of the yields obtained within each row. Furthermore, the yield range (maximum corn grain yield minus the minimum corn grain yield per row) was found to increase with increasing yield level. Regardless of yield level, plant-to-plant variability in corn grain yield can be expected and averaged more than 2765 kg ha^{-1} over sites and years. Averaging yield over distances >0.5 m removed the extreme by-plant variability, and thus, the scale for treating other factors affecting yield should be less than 0.5 m. Methods that homogenize corn plant stands and emergence may decrease plant-to-plant variation and could lead to increased grain yields.

Variability in plant stands is well documented. Nielsen (2001) studied plant-spacing variability (PSV) in 354 commercial fields of corn throughout Indiana and Ohio. This work showed that the standard deviation of plant spacing was 7.5 cm or less in only 16% of the fields. Sixty percent of the sampled fields exhibited standard deviations of plant spacing between 10 and 12.5 cm. Plant-spacing standard deviations in 24% of the fields were 15 cm or greater (up to 30 cm). Their results showed that for every 2.54 cm increase in the standard deviation in plant-to-plant spacing, 156 kg ha^{-1} (2.5 bu ac^{-1}) in grain yield was lost. The average standard deviation of plant spacing was 17.2 cm (6.8 in), resulting in an estimated 1066 kg ha^{-1} (17 bu ac^{-1}) yield loss over 354 commercial fields. Lauer and Rankin (2004) and Liu et al. (2004) had differing results, noting that PSV did not significantly alter grain yields in Wisconsin and Ontario, Canada, respectively. Nafziger et al. (1991) noted that uneven emergence of corn can occur when soils are dry at the time of planting and could lead to decreased grain yields. It is generally accepted that when adjacent plants differ by more than two leaf stages, the younger plant may not develop to its fullest potential. A two leaf stage difference can result from delayed emergence ranging from 5 to 10 d, which can cause a 1% yield loss for each 1-d delay (Robert L. Nielsen, Purdue University, personal communication, 2004). Tollenaar and Wu (1999) found increased stress tolerance in corn when plant-to-plant variability was lower. In general, these statistics identify a twofold problem: first, the need to homogenize plant spacing and emergence and second, the need to recognize differences in yield potential that clearly exist by plant.

Some technologies in precision agriculture have been driven commercially. The most notable has been combine yield monitors. Depending on combine speed, header width, and the smoothing effect as grain moves through the combine, each sensed element represents more than 48 m^2 (width of swath times the distance traveled in 2 to 4 s). However, Lengnick (1997), Solie et al. (1999), and Raun et al. (1998) found significant soil variability at distances less than 30 m apart, and in many cases, less than 1 m. Furthermore, large differences in measured yield have been reported on a small scale (<0.4 m^2) for winter wheat (*Triticum aestivum* L.) (Raun et al., 2002) and by plant in corn (Raun et al., 2005). For corn, the expressed spatial variability was greatest at the V6 growth stage (Ritchie et al., 1996). This peak in the within-row variability was thought to occur at the same growth stage where treating the variability would have the greatest impact (Raun et al., 2005). Maddonni and Otegui (2004) reported that the greatest difference in estimated shoot biomass between plant types occurred between V7 and V13 (Ritchie et al., 1996) and remained constant from V13 onward. Vega and Sadras (2003) found a strong inequality in reproductive output within high populations of corn, indicating an apparent breakage of reproductive allometry.

Varvel et al. (1997) noted that when sufficiency indices (determined with a SPAD meter) were lower than 90% at V8, maximum yields were not achieved with in-season N fertilizer applications because early-season available N was below that needed for optimum growth

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Abbreviations: CV, coefficient of variation; NDVI, Normalized Difference Vegetative Index = $(\rho_{NIR} - \rho_{Red})/(\rho_{NIR} + \rho_{Red})$; PSV, plant-spacing variability.

and yield potentials had already been reduced. Therefore, if added N was needed, making the decision to apply should likely take place at or before V8.

Fundamental field element size is the area where maximum relatedness exists between adjacent elements. Treatment at scales larger than the fundamental field element size compromises the effectiveness since independent variation of nutrient levels exists within a single treatment level. Treatment at scales less than the fundamental field element size is pointless, as nutrient levels within this scale are related. When N decisions are at 1-m^2 resolution, the variability present can be detected (e.g., Normalized Difference Vegetative Index, or NDVI) and treated accordingly with foliar N (Solie et al., 1996; Stone et al., 1996), thus increasing N use efficiency. Taylor et al. (1999) reported that smaller plot sizes employed in variety trials reduced the variability encountered in estimating the mean yield. This was consistent with the resolution where detectable differences in soil test parameters exist that should be treated independently.

Porter et al. (1998) observed that temporal yield variability was approximately three times greater for soybean [*Glycine max* (L.) (Merr.)] and four times greater for corn than spatial variability among plots. They also reported that producers should not change management practices (as a function of yield maps) unless the differences were shown to be consistent over years. Mallarino et al. (1999) employed grid sampling and factor analysis to investigate the relationship between several site variables (soil tests, plant population, weed control, etc.) and corn grain yields in five producer fields. They reported that some of the variables collected were correlated with grain yields, but that the relationships changed between fields. When collecting corn grain yield data from twenty-four 4.6- by 3.0-m subplots within a larger farmer field, Schmidt et al. (2002) showed that yields ranged from 4.7 to 9.5 Mg ha^{-1}. It is important to note that this large range in yield was from plots that did not receive any fertilizer N. They also noted that variable N application is needed to achieve maximum grain yield and improved N management over different locations in the same field. Sadler et al. (1998) noted that Coastal Plain soils required study at finer resolutions than the >100-m grids commonly used in precision farming.

The objectives of this study were (i) to evaluate by-plant corn grain yield variability over a range of production environments; (ii) to determine the relationships among mean grain yield, standard deviation of yield, coefficient of variation (CV) of yield, and yield range; and (iii) to evaluate the relationship between NDVI and corn grain yields.

MATERIALS AND METHODS

In accordance with the countries and states where data were collected for this paper, the following production statistics are provided. In 2003, world corn grain production averaged 4.5 Mg ha^{-1}, coming from 142 million ha. Average corn grain yields in the USA, Argentina, and Mexico were 8.9, 6.4, and 2.5 Mg ha^{-1} from 28, 2.3, and 7.8 million ha, respectively (http://faostat.fao.org; verified 19 Aug. 2005). In Iowa, Nebraska, Ohio, Virginia, and Oklahoma, average corn grain yield for 2003 was 9.8, 9.2, 8.7, 7.2, and 7.8 Mg ha^{-1} from 4.8, 3.1, 1.2, 0.13, and 0.08 million ha, respectively (www.usda.gov/nass/nasshome.htm; verified 19 Aug. 2005).

By-plant harvested corn grain yields from 13 different sites in Argentina, Mexico, Iowa, Nebraska, Ohio, Virginia, and Oklahoma were evaluated to determine relationships among by-plant and averaged yield and ranges, standard deviations, and coefficients of variation of yields. At each location, corn rows (transects) ranging from 8 to 30 m in length were selected for by-plant harvesting. At most of the sites, individual plants were marked at or before the V8 growth stage to ensure detection of barren and/or lost plants at harvest (60–85 d later depending on the maturity). At the same time that plants were tagged, a tape measure was extended the length of the row, and cumulative distances were recorded for each plant.

At most sites, based on the row spacing used at each location, the area occupied by each plant was calculated. This was done by assuming that each plant occupied half the distance to and from its nearest neighbor (Eq. [1]):

$$A_i = \left[\frac{d_i - d_{i-1}}{2} + \frac{d_{i+1} - d_i}{2}\right]R \qquad [1]$$

where A_i is the area occupied by the ith plant; d_{i-1}, d_i, and d_{i+1} are the distances to the $i - 1$, i, and $i + 1$ plants; and R is the row spacing.

Each ear was harvested individually from each plant and the weight recorded. When more than one ear per plant was present, total weight was recorded on a by-plant basis. At those sites where actual distances between plants were not recorded, an average distance occupied per plant was determined based on row spacing and total transect or row distance and number of plants harvested per row. Once removed from the stalk, ears were dried at 66°C for 48 h and weighed before and after shelling. The dry grain weight taken from the shelled corn was the final weight used for yield determination. The locations sampled, number of transects at each site, planting date, harvest date, row spacing, plant population, hybrid, and maturity are reported in Table 1. Location, soil series, texture, and transect length are included in Table 2. At some of the sites, NDVI data were collected at the V8 growth stage, directly over the corn row using a shaft encoding GreenSeeker sensor placed 76 cm above the corn canopy and that was capable of recording NDVI readings with computed distance every 0.5 cm. Sensor NDVI readings were then averaged for consecutive four-plant clusters. Corn ears from these four-plant clusters were harvested and shelled to evaluate the relationship between NDVI readings at V8 and final grain yield.

Statistical analysis included regression of average grain yield per transect on the standard deviation, CV, and yield range of by-plant grain yield over all locations using SAS (SAS Inst., 2002). The areas where by-plant harvest data were collected were representative of a range of corn production environments around the world. The previous crop and tillage practice employed at each site are reported in Table 2.

RESULTS

Average transect corn grain yield plotted against standard deviation, CV, and yield range over all locations is illustrated in Fig. 1, 2, and 3, respectively. Prediction equations reported and plotted on Fig. 1–3 do not exceed the limits of the collected data. The standard deviation of by-plant corn grain yield increased with increasing yield level up to 13 000 kg ha^{-1} (Fig. 1). This is consistent with several sources reporting that the stan-

Table 1. Location, transect, year, planting date, harvest date, row spacing, plant population, and corn hybrids where corn grain yields were evaluated by plant from 2002 to 2004 from transects ranging from 8 to 30 m of row, USA, Argentina, and Mexico.

Location	Transect	Year	Planting date	Harvest date	Row spacing	Plant population	Maturity	Hybrid
					cm	plants ha^{-1}	d	
El Batan, Mexico	1	2002	24 July 2002	4 Dec. 2002	76	62 656	125	CMS-939083
El Batan, Mexico	1	2002	24 July 2002	4 Dec. 2002	76	62 656	125	CMS-939083
El Batan, Mexico	2	2002	24 July 2002	4 Dec. 2002	76	62 656	125	CMS-939083
El Batan, Mexico	3	2002	24 July 2002	4 Dec. 2002	76	62 656	125	CMS-939083
Lake Carl Blackwell, OK	3	2003	8 Apr. 2003	11 Aug. 2003	76	32 918	104	Pioneer†
Lake Carl Blackwell, OK	4	2003	8 Apr. 2003	11 Aug. 2003	76	30 056	104	Pioneer†
EFAW, OK	2	2003	31 Mar. 2003	5 Aug. 2003	76	53 689	111	Asgrow†
EFAW, OK	1	2003	31 Mar. 2003	5 Aug. 2003	76	53 043	111	Asgrow†
EFAW, OK	3	2003	31 Mar. 2003	5 Aug. 2003	76	49 403	111	Asgrow†
EFAW, OK	4	2003	31 Mar. 2003	5 Aug. 2003	76	50 412	111	Asgrow†
Lake Carl Blackwell, OK	1	2004	27 Apr. 2004	2 Aug. 2004	76	60 735	108	Pioneer Bt†
Lake Carl Blackwell, OK	2	2004	3 Apr. 2004	2 Aug. 2004	76	63 072	108	Pioneer Bt†
Lake Carl Blackwell, OK	3	2004	27 Apr. 2004	2 Aug. 2004	76	37 287	108	Pioneer Bt†
Lake Carl Blackwell, OK	4	2004	3 Apr. 2004	2 Aug. 2004	76	35 496	108	Pioneer Bt†
Lake Carl Blackwell, OK	5	2004	3 Apr. 2004	2 Aug. 2004	76	57 243	108	Pioneer Bt†
Lake Carl Blackwell, OK	6	2004	27 Apr. 2004	2 Aug. 2004	76	57 572	108	Pioneer Bt†
Hennessey, OK	2	2004	27 Apr. 2004	13 Sept. 2004	76	35 511	113	Pioneer Bt†
Hennessey, OK	1	2004	27 Apr. 2004	13 Sept. 2004	76	36 166	113	Pioneer Bt†
EFAW, OK	1	2004	7 Apr. 2004	27 Aug. 2004	76	65 846	113	Pioneer Bt†
EFAW, OK	1	2004	7 Apr. 2004	25 Aug. 2004	76	65 429	108	Pioneer Bt†
EFAW, OK	2	2004	7 Apr. 2004	25 Aug. 2004	76	70 942	108	Pioneer Bt†
EFAW, OK	3	2004	7 Apr. 2004	25 Aug. 2004	76	36 259	108	Pioneer Bt†
EFAW, OK	4	2004	7 Apr. 2004	25 Aug. 2004	76	37 799	113	Pioneer Bt†
Perkins, OK	1	2004	2 Apr. 2004	27 Aug. 2004	76	48 410	108	Pioneer Bt†
Ames, IA	east	2004	10 May 2004	24 Sept. 2004	76	55 808	105	Pioneer 35P17
Ames, IA	west	2004	10 May 2004	24 Sept. 2004	76	68 018	105	Pioneer 35P17
Shelton, NE	1	2004	7 May 2004	13 Oct. 2004	91	72 778	118	Pioneer 31N27
Shelton, NE	2	2004	7 May 2004	13 Oct. 2004	91	71 590	118	Pioneer 31N27
Wooster, OH	1	2004	7 May 2004	25 Oct. 2004	76	70 395	111	Bird B64
Parana, Argentina	1–4–5	2003	16 Sept. 2003	20 Feb. 2003	70	90 578	120	Dekalb 682 MG
Parana, Argentina	12–13–14	2003	16 Sept. 2003	20 Feb. 2003	70	88 786	120	Dekalb 682 MG
Parana, Argentina	16–17–20	2003	16 Sept. 2003	20 Feb. 2003	70	89 795	120	Dekalb 682 MG
Parana, Argentina	21–22–25	2003	16 Sept. 2003	20 Feb. 2003	70	94 978	120	Dekalb 682 MG
Parana, Argentina	31–33–35	2003	16 Sept. 2003	20 Feb. 2003	70	93 185	120	Dekalb 682 MG
Parana, Argentina	41–42–43	2003	16 Sept. 2003	20 Feb. 2003	70	90 015	120	Dekalb 682 MG
Parana, Argentina	46–49–50	2003	16 Sept. 2003	20 Feb. 2003	70	92 378	120	Dekalb 682 MG
Parana, Argentina	56–57–60	2003	16 Sept. 2003	20 Feb. 2003	70	93 595	120	Dekalb 682 MG
Painter, VA	1,5,9	2003	5 May 2003	17 Sept. 2003	76	69 136	120	Pioneer 32R25
Painter, VA	2,6,10	2003	5 May 2003	17 Sept. 2003	76	69 136	120	Pioneer 32R25
Painter, VA	3,7,11	2003	5 May 2003	17 Sept. 2003	76	69 136	120	Pioneer 32R25
Painter, VA	4,8	2003	5 May 2003	17 Sept. 2003	76	69 136	120	Pioneer 32R25
Phillips, NE	1–2	2004	1 May 2004	8 Nov. 2004	76	66 810	116	Pioneer 32T78
Phillips, NE	3–4	2004	1 May 2004	8 Nov. 2004	76	64 655	116	Pioneer 32T78
Phillips, NE	5–6	2004	1 May 2004	8 Nov. 2004	76	66 810	116	Pioneer 32T78
Phillips, NE	7–8	2004	1 May 2004	8 Nov. 2004	76	72 198	116	Pioneer 32T78
Phillips, NE	9–10	2004	1 May 2004	8 Nov. 2004	76	64 655	116	Pioneer 32T78

† Experimental hybrid donated by Pioneer and Asgrow; actual number not made available.

dard deviation of yields increases with increasing yield level (Taylor et al., 1999; Dobermann et al., 2003). The CV of by-plant yields was negatively correlated with mean grain yield across the range of experiments studied (Fig. 2). The test for the slope (negative) being different from zero was highly significant ($P > |t|$, 0.0007). Even

Table 2. Soil series and texture from location transects ranging from 8 to 30 m of row, USA, Argentina, and Mexico.

Location	Site-year	Soil series	Previous crop	Tillage	Soil texture	Meters per transect
						m
El Batan, Mexico	2002	Fluventic Hapludoll	wheat	conventional	silt loam	27
Lake Carl Blackwell, OK	2003	Port-oscar	corn	conventional	silt loam	30
EFAW, OK	2003	Easpur	wheat	conventional	loam	30
Lake Carl Blackwell, OK	2004	Port-oscar	corn	conventional	silt loam	30
Hennessey, OK	2004	Shellabarger	corn	conventional	sandy loam	30
EFAW, OK	2004	Easpur	corn	conventional	loam	30
EFAW, OK	2004	Easpur	corn	conventional	loam	13.5
Perkins, OK	2004	Teller	corn	conventional	sandy loam	10
Ames, IA	2004	Clarion	corn	conventional	loam	23, 19†
Shelton, NE	2004	Hord	corn	conventional	silt loam	15, 19†
Wooster, OH	2004	Canfield	soybean	no-till	silt loam	8.1
Parana, Argentina	2003	Tezanos Pinto	soybean	no-till	silt loam	10.5‡
Painter, VA	2003	Bojac	potato	conventional	sandy loam	9.1
Phillips, NE	2004	Ully	corn	conventional	silt loam	12.2§

† Transect length was different for each row at these sites.
‡ Designates locations where three rows, side by side, were combined to form a larger transect.
§ Designates locations where two rows, side by side, were combined to form a larger transect.

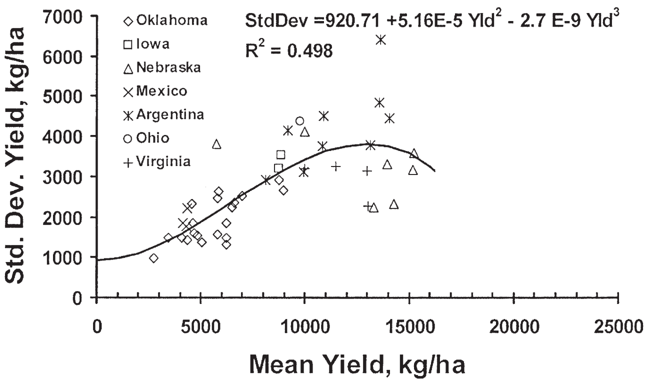

Fig. 1. Average corn grain yield plotted against the standard deviation from by-plant yield over 46 transects in Argentina, Mexico, Iowa, Nebraska, Ohio, Virginia, and Oklahoma.

though CVs were lower for the higher-yielding sites, the actual plant-to-plant variation in grain yield (kg ha^{-1}) was greater when compared with sites with lower average yields. The yield range (maximum yield observed in each transect minus the minimum yield observed) increased with average corn grain yields (Fig. 3).

Average grain yield across all regions ranged from 4268 to 14 383 kg ha^{-1}, with an average of 8495 kg ha^{-1} (135 bu ac^{-1}), close to the U.S. average and above that for Argentina and Mexico (Table 3). The average differences in measured yield plant to plant ranged from 1724 to 4367 kg ha^{-1} (excluding barren plants) and averaged 2765 kg ha^{-1} (44.1 bu ac^{-1}) (Table 3). At those sites where the average yields were the highest (Phillips, NE, and Argentina), the standard deviations about the yield mean were 2926 kg ha^{-1} (47 bu ac^{-1}) and 4211 kg ha^{-1} (67 bu ac^{-1}), respectively. Although a trend for decreased CVs at the higher yield levels was observed (Fig. 2), the average plant-to-plant yield differences that would be encountered at both these high-yielding sites exceeded the average over all locations where yields were much lower.

DISCUSSION

The sites reported in this paper were planted and treated using normal practices in each region. No steps were taken to minimize cultural, nutrient, or environmental factors that would keep the corn hybrids from

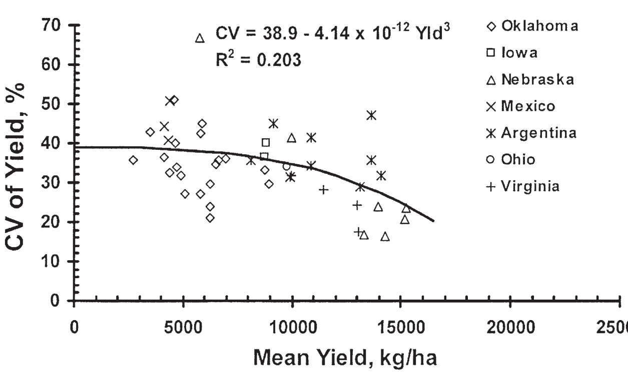

Fig. 2. Average corn grain yield plotted against the coefficient of variation from by-plant yields over 46 transects in Argentina, Mexico, Iowa, Nebraska, Ohio, Virginia, and Oklahoma.

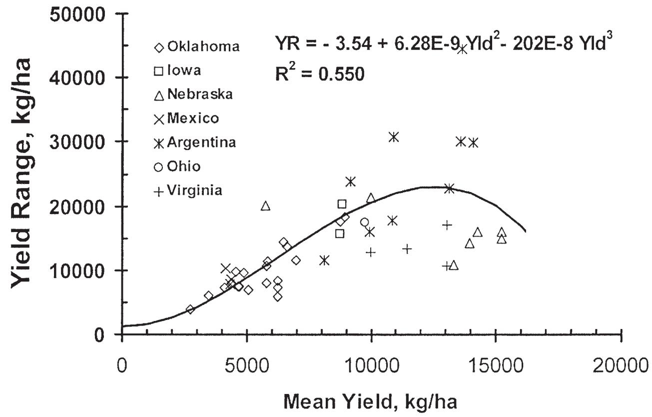

Fig. 3. Average corn grain yield plotted against the by-plant yield range (maximum minus minimum yield) in 46 transects ranging from 10.5 to 30 m in length in Argentina, Mexico, Iowa, Nebraska, Ohio, Virginia, and Oklahoma.

achieving their genetic yield potential. To achieve the theoretical maximum genetic yield potential, stands must be optimum, plant spacing must be exact, seed must be planted at ideal and uniform depth, germination should be 100%, all nutrients must be nonlimiting, soil types and physical properties must be uniform and ideal for the cultivar, and moisture, temperature, and all other environmental factors must be ideal during the entire growing season. All plants must emerge within 1 d. All plants must set at least one ear of corn, and the ear must completely fill. Under these conditions, the range of yield and standard deviation of yield should theoretically approach zero.

Causes for the Large Differences in By-Plant Corn Grain Yields

There are many variables that likely contributed to the extensive variability in by-plant corn grain yield seen at all sites included in this study. Delayed and uneven emergence can be caused by variable depth of planting, wheel compaction, location of the seed within the furrow, surface crusting, random soil clods, soil texture differences, variable distance between seeds, seed germination, variable soil compaction around the seed, insect damage, moisture availability, variable surface residue, variable seed furrow closure, and/or many other factors that influence nonuniformity of plants. In light of the many factors known to influence plant stands, within-row variability in corn grain yield should be expected, and that was present in the trials evaluated here. In all trials, common hybrids were employed for each respective region. Each row was inspected early in the season (excluding the Phillips, NE location) for volunteer corn, and these plants were removed. The presence of volunteer corn plants was scarce, especially in Virginia, Argentina, Mexico, Ohio, and some sites in Oklahoma where corn was not the previous crop (Table 2).

The range of average yields (2700–16 100 kg ha^{-1}) included in this study was representative of a wide array of production environments (Fig. 1–3). Some of these sites were irrigated while others relied on natural precipitation. One of the sources of plant-to-plant variability

Table 3. Minimum, maximum, mean, standard deviation, maximum/minimum, and coefficient of variation (CV) for by-plant corn grain yields from 46 transects in Argentina, Mexico, Iowa, Nebraska, Ohio, Virginia, and Oklahoma, 2002–2004.

Location	Years	Transects	Min. yield	Max. yield	Mean yield	SD	Max./min.	CV
			kg ha^{-1}					%
El Batan, Mexico	2002	3	606	9 440	4 268	1935	22.4	45.3
OK, <6000 kg ha^{-1}	2003–2004	12	1128	9 169	4 652	1724	10.0	37.2
OK, >6000 kg ha^{-1}	2003–2004	8	1947	14 120	7 050	2167	11.6	30.5
Ames, IA, Shelton, NE	2004	4	1872	21 173	8 320	3660	14.1	46.0
Wooster, OH	2004	1	2066	19 458	9 759	4367	9.4	50.2
Parana, Argentina	2003	9	2806	28 058	11 478	4211	15.0	36.8
Painter, VA	2003	4	4753	24 552	11 943	3171	5.2	26.7
Phillips, NE	2004	5	7098	21 492	14 383	2926	3.2	20.3
All sites	2002–2004	46	2752	17 281	8 495	2765	11.1	34.3

could be competition for soil moisture, especially in dryland fields. However, this would be an unlikely source of plant-to-plant variability at the higher yield levels where moisture was not limiting (>13 000 kg ha^{-1}), unless soil texture differences were expected at the by-plant level. Similarly, the extensive plant to-plant differences in grain yield within 8 to 30 m of row were unlikely due to plant-to-plant differences in early-season N availability.

Maddonni and Otegui (2004) noted that increased interplant competition in corn hybrids enhanced the appearance of plants with different competitive abilities. Thus at higher populations, plant-to-plant variation can also be expected. They noted that the onset of interplant competition started very early during the life cycle and that differences in estimated plant biomass between stand densities were detected as early as V6. Furthermore, they reported that plant population and row-spacing treatments alone did not modify the onset of the hierarchical growth among plants. The same causes for delayed and uneven emergence discussed earlier in this section would likely be expressed later in the life cycle with variable plant growth.

Expression of Variability

Seed suppliers do not normally publish genetic yield potential data (Fig. 1–3). However, the National Corn Growers Association Corn Yield Contest results (www.ncga.com/02profits/CYC/winners/winners.html; verified 19 Aug. 2005) can serve as a surrogate for these data. To achieve maximum yields, contest participants attempt to manage all factors under their control to minimize reduction in corn yield from the cultivars' genetic yield potential. The highest first-place yields for all classes from 2002, 2003, and 2004 ranged from 19 000 to 22 000 kg ha^{-1}.

Nonlinear equations were fitted to the data using Table Curve 2D (Systat Software, 2000). The equations with the highest R^2, which conformed to the upper and lower boundary conditions, were selected. In all cases, a partial cubic polynomial model met these requirements, and that was fit using a zero intercept. Examination of Fig. 1 through 3 yielded the following additional observations on the relationship of average corn yield to CV, range, and standard deviation. The range and standard deviation curves peaked near 13 000 kg ha^{-1}. The corn by-plant yield CV was nearly constant for yields under 10 000 kg ha^{-1} and declined moderately to 15 000 kg ha^{-1}. Average field scale corn yields in all areas reported in this paper were generally much lower than 15 000 kg ha^{-1}. The by-plant corn yield variability was large within the yield ranges achieved by producers, as indicated by the state and country averages cited previously. Because the overall plant-to-plant variation in yield was found to be 2765 kg ha^{-1} (44.1 bu ac^{-1}) (Table 3), it will likely be important to recognize and treat these differences. If it is feasible to recognize 2765 kg ha^{-1} plant-to-plant yield differences when average yields are 4300 kg ha^{-1}, it should be feasible to detect them when average yields are 14 000 kg ha^{-1}.

Errors Associated with By-Plant Yield

Using the average plant yield of 120 g (dry shelled weight) over all trials included in this study and randomly applying all the errors included in the estimate (scale precision of 0.05 g, by-plant tape measure precision of 1.0 cm, and row spacing error of 1 cm), the yield estimate was 645 g m^{-2} or 6453 kg ha^{-1}, which would be off by 5.8% when compared with the true value with no errors (6073 kg ha^{-1}) using a 26-cm distance between plants and a 76-cm row spacing. Similarly, a 5.2% error was found when estimating yield from larger plots (harvesting two rows, 13.6 m in length) using a field plot combine [plot weight of 10.5 ± 0.2 kg (on-board scale precision) and a row distance of 13.6 ± 0.2 m, row spacing of 76 ± 1 cm]. This suggests that estimates of by-plant yields are no more problematic than small plot work using all the respective errors.

Work by Taylor et al. (1999) showed that standard deviations about yield means increased as mean yields increased in 220 fertilizer, weed management, and tillage trials, and that was similarly encountered in the trials reported here. Also, Taylor et al. (1999) reported a decrease in yield CV when mean yields increased. However, unlike the work of Taylor et al. (1999), which focused on plot data, we report on the standard deviations associated with by-plant differences in measured grain yield.

The average maximum/minimum range observed was 11× (46 transects ranging from 8 to 39 m of row) (Table 3). This came from experiments with an average yield of 8495 kg ha^{-1}, well above the world average of 4500 kg ha^{-1} reported for corn grain yield in 2003. Furthermore, the data collected at specific sites within each location (Argentina, Mexico, Iowa, Nebraska, Ohio, Virginia, and Oklahoma) had yields equal to or

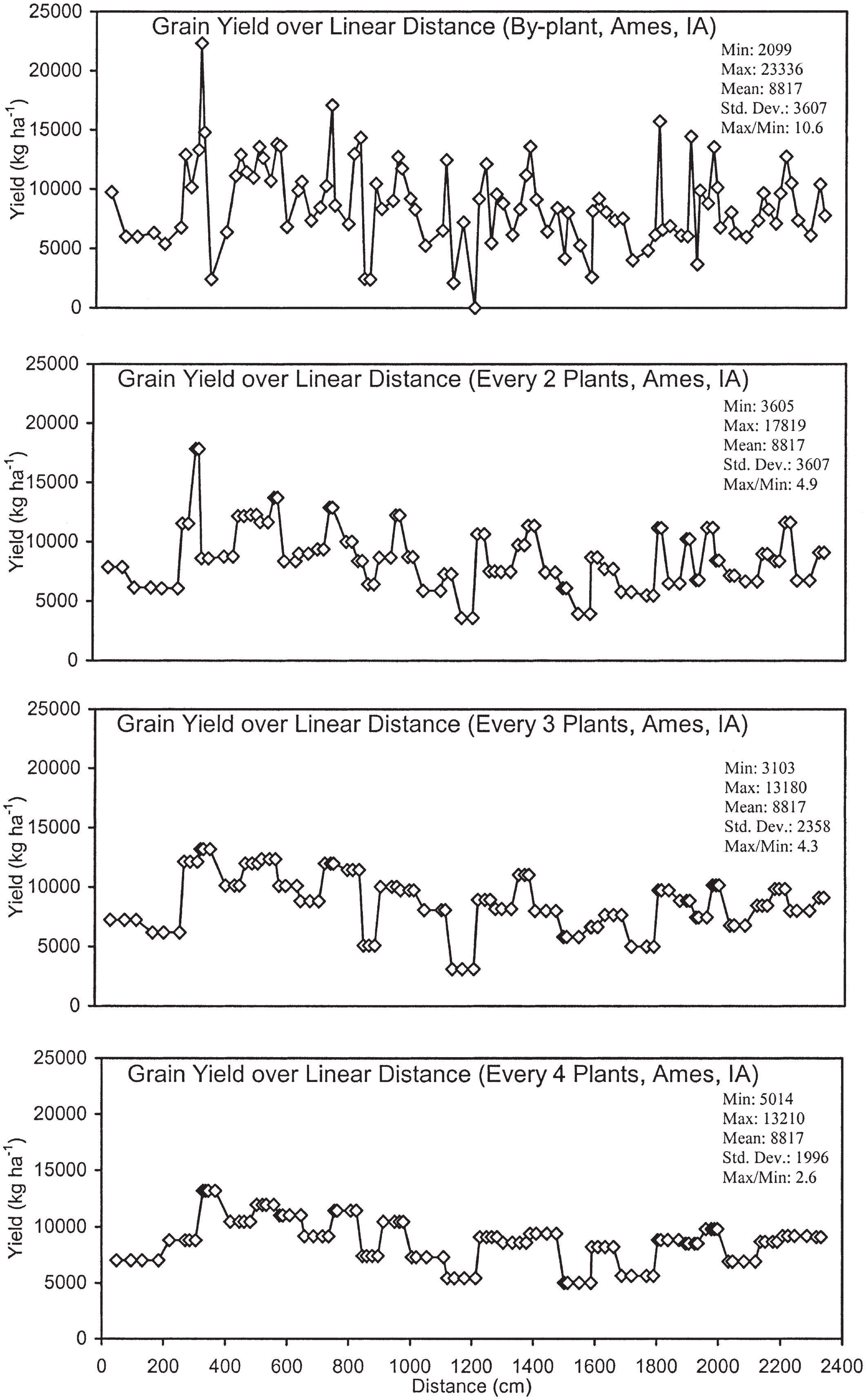

Fig. 4. Average corn grain yields plotted by plant, every two plants, every three plants, and every four plants, using measured distances between plants at Ames, IA in 2004.

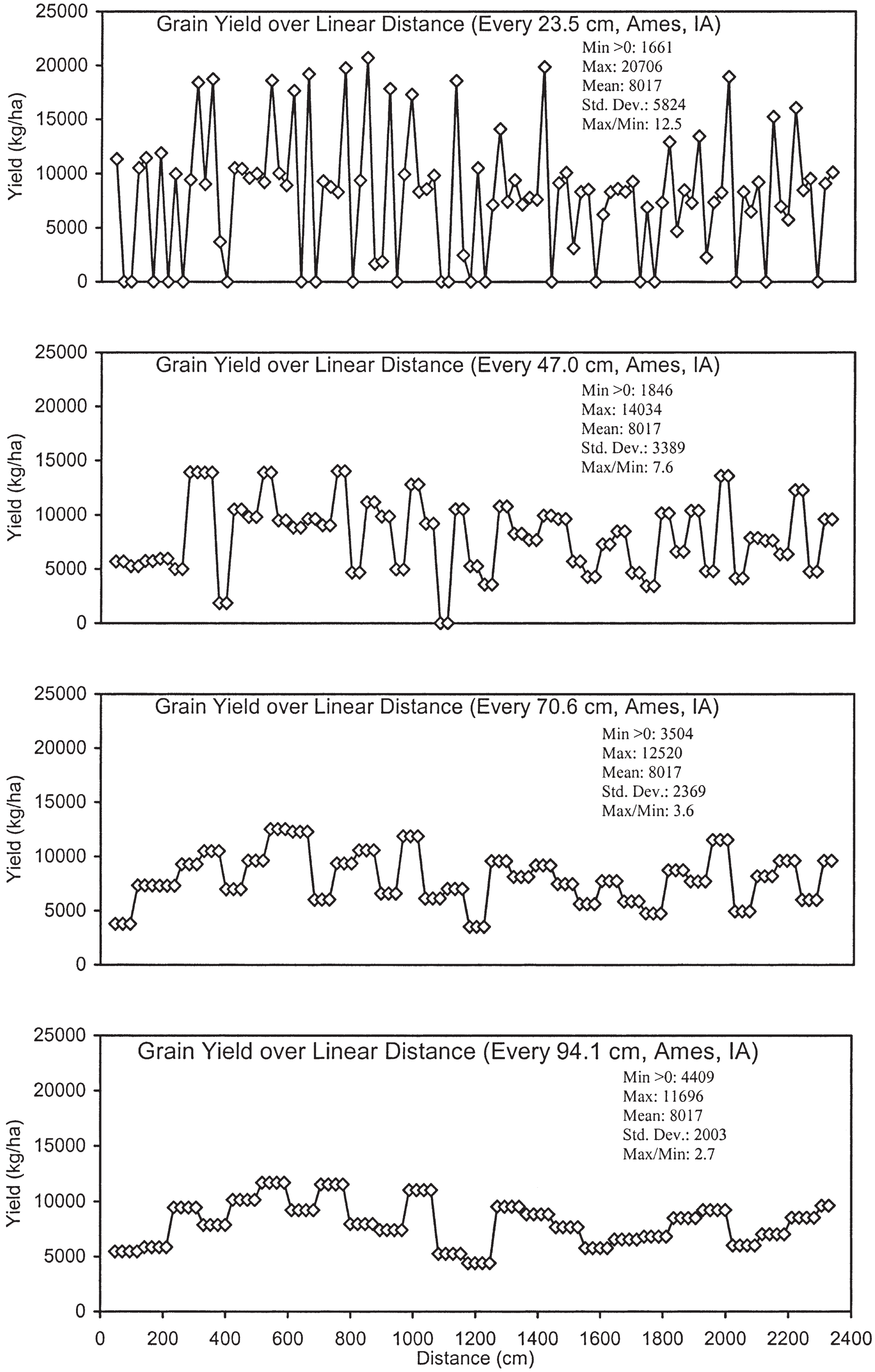

Fig. 5. Average corn grain yields computed using fixed distances of 23.5, 47.0, 70.6, and 94.1 cm at Ames, IA in 2004.

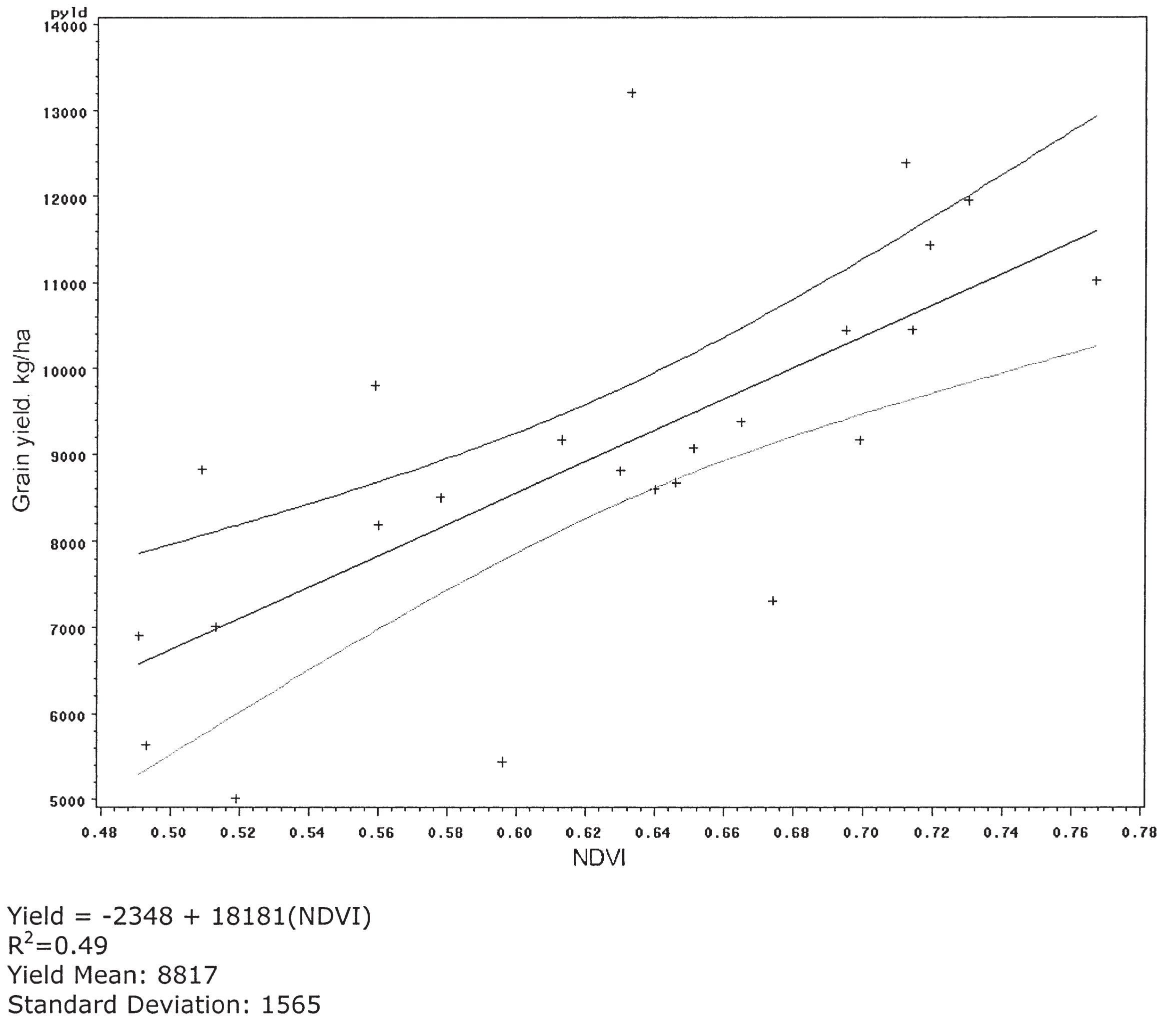

Fig. 6. Normalized Difference Vegetative Index (NDVI) versus corn grain yield determined for every four plants using linear regression and associated 95% confidence intervals, east row at Ames, IA in 2004.

exceeding each specific region's average. Dobermann et al. (2003) reported corn grain yields from 4- by 4-m grids determined from yield monitor data from 1996 to 2001. In this work, the maximum/minimum yields observed in the entire field exceeded 20×.

Table 4. Absolute value of the errors in estimating by-plant corn yield by averaging yield over a fixed distance along the row.

Distance	Mean error	Maximum error	Minimum error
cm		Shelton, NE	
15.0	5254	19 562	0
30.0	4401	19 562	65
45.1	3877	14 961	13
60.1	3687	11 249	12
75.1	3906	17 271	24
90.1	3784	14 170	3
1503	3569	1 392	55
		Ames, IA	
23.5	5497	22 336	83
47	3588	17 347	7
70.5	3101	16 191	14
94	2937	15 233	93
2352	2798	13 519	7
		EFAW, OK	
20.1	3283	14 634	0
40.1	2538	8 962	56
60.2	2166	8 227	76
80.2	2023	9 207	15
100.3	2280	10 030	15
2989	2473	10 569	10

Corn Grain Yields Averaged over Larger Scales

If it were not possible to recognize each plant individually using sensors as has been published, it would be

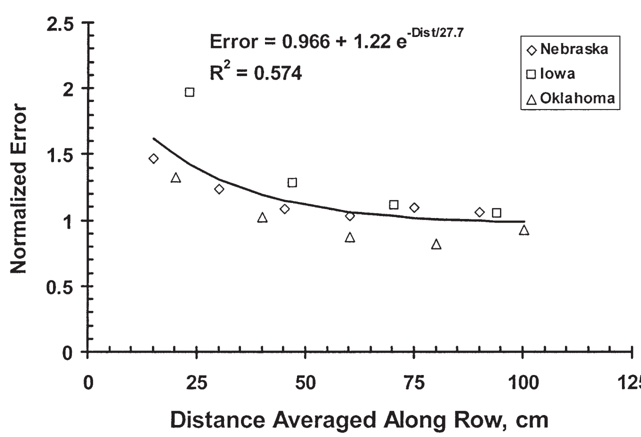

Fig. 7. Effect of averaging plant yields over a specified distance along the row on the absolute error incurred when using the average corn yield for estimating the by-plant yield. Yields were normalized by the average yield along the entire row.

considered important to evaluate the error in predicting by-plant yields when yields were averaged over different scales, either by more than one plant or by a fixed distance. To investigate this, by-plant grain yields were averaged over two, three, and four plants in 15 m of row from the Ames, IA location (Fig. 4). The largest differences in corn yield were discernable at the by-plant level. However, 4.9, 4.3, and 2.6× differences were detected within 15 m of row when averaged over two, three, and four plants, respectively (Fig. 4). At this site, the average differences in yield (standard deviation) were 3607, 2678, 2358, and 1996 kg ha^{-1} when yields were averaged over one, two, three, and four plants. When averaged over every four plants, this scale resulted in average differences between four-plant clusters that exceeded 1900 kg ha^{-1} (30 bu ac^{-1}). In addition, when evaluating every four-plant cluster in 15 m of row, the range in yields was 5014 to 13 210 kg ha^{-1} (difference of 8196 kg ha^{-1} or 131 bu ac^{-1}).

For the data in Fig. 4, grain yields were determined based on actual measured distances between plants and the area calculated from Eq. [1], which resulted in 10.6× differences in corn grain yield over 15 m of row. However, it is important to note that when by-plant grain yields were computed based on a fixed area (average distance between plants, 23.5 cm, over the entire row), a 12.5× difference in yield differences was observed at the Ames, IA site (Fig. 5). At all sites, large differences in corn grain yield were observed over short distances whether or not grain yields were computed based on actual measured distances or an average (fixed) distance between plants.

At the Ames, IA site, midseason prediction of corn grain yields (same four-plant clusters) was quite good using NDVI collected at the V8 growth stage (Fig. 6). The average yield difference of 1996 kg ha^{-1} between each four-plant cluster was greater than the precision at which final grain yields could be predicted midseason using NDVI (precision of ± 1565 kg ha^{-1}).

Errors in Corn Grain Yields from Larger Scales

Yet another alternative approach concerning this data was evaluating the errors associated with yield determined over fixed distances in a row (EFAW experiment station near Stillwater, OK; Shelton, NE; and Ames, IA). The distances used to calculate the yields were determined by dividing the total length of the row by the number of plants in the row. The yields were then averaged over multiples of that distance until the distance approached 1 m. Then, the absolute value of the errors in estimating the by-plant corn yield from the average value of the yields along fixed distances were calculated. Table 4 shows the mean, minimum, and maximum error associated with the fixed-distance yield calculation. At each location, the errors in the by-plant yield prediction decreased as yields were averaged over greater distances, with errors approaching a constant as distances approached 1 m (Fig. 7). The distance where the true yield mean of the row could be estimated was between 0.5 to 0.6 m. All sites behaved similarly, with similar normalized errors in the by-plant yield estimates. Even though there are errors associated with predicting yield at early growth stages (V8, Fig. 6), these errors in yield prediction were dwarfed in comparison to the by-plant yield differences reported.

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