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Maize grain yield responses to plant height variability resulting from crop rotation and tillage system in a long-term experiment

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ABSTRACT

Research emphasizing slower plant growth and delayed maturity in continuous maize (*Zea mays* L.), no-till (MM–NT) systems has often led to the conclusion that lower grain yields in this environment are associated with reduced plant heights. Yet prior research has shown that early-season and mature plants are not always shorter in MM–NT systems, suggesting that overall plant height may not be an accurate morphometric indicator of decreased yield in MM–NT environments. Given that plant-to-plant morpho-physiological uniformity is strongly associated with higher yield in maize, we hypothesized that greater plant height variability would provide a better agronomic explanation for yield loss in MM–NT environments than overall plant height reductions. This 14-year study primarily examined the effects of crop rotation {maize–soybean [*Glycine max* (L.) Merr.] and continuous maize} and tillage system (no-till and moldboard plow) on the yield, 4-week plant population, and 4- and 8-week plant height and plant height variability of a single maize cultivar. Due to sizeable year-to-year variation, actual crop response means for the MM–NT; maize–soybean, no-till (MB–NT); and continuous maize, moldboard plow (MM–PL) treatment combinations were expressed relative to the accompanying means for the maize–soybean, moldboard plow (MB–PL) treatment. In numerous years, the MM–NT system exhibited reduced actual and relative yields and lower 4- and 8-week plant heights compared to the other treatment combinations. Both actual and relative 4- and 8-week plant height variability were rarely greatest for the MM–NT treatment, and in only a few years were actual and/or relative plant density lowest for this system. However, single-factor regression analyses between relative yield and the aforementioned relative agronomic measures revealed that a decline in relative MM–NT yield was most strongly associated with an increase in relative 4-week plant height variability. Multi-factor regression analyses between relative yield, relative 4-week plant height variability, and various weather parameters suggested that this strong inverse relationship was potentially a manifestation of (i) non-uniform germination, emergence, and early seedling growth and (ii) later-season intra-specific competition. Regression analyses between relative 4-week plant height variability and various weather parameters suggested that phenomenon (i) was potentially promoted by cool and moist or warm and dry pre-plant weather conditions while phenomenon (ii) was possibly encouraged by low precipitation and/or high temperatures during rapid stem elongation. While MM–NT systems should be managed to limit plant density reductions and minimize growth and developmental delays, increased focus should be placed on minimizing the occurrence of plant-to-plant variability in these environments.

1. Introduction

Across field crop species, growers in the United States are increasingly adopting conservation tillage systems (e.g., no-till, ridge-till, and mulch-till systems) (CTIC, 2006a) as they search for ways to cut production costs, reduce soil erosion, improve overall soil health [e.g., soil structure, ecology, and organic matter (SOM) content] (Kladivko, 1994), and lessen negative environmental impacts [e.g., CO_2, N_2O, and CH_4 emissions (Six et al., 2004)]. Despite the documented benefits of conservation tillage practices, the adoption of these systems for US maize (*Zea mays* L.) production has not generally increased in recent years. In fact, the use of tillage systems in maize leaving greater than 30% residue cover (i.e., conservation tillage systems) fell from 1994 to 2002 and

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only slightly increased from 2002 to 2004 (CTIC, 2006b). Actual or perceived problems in maize grown using conservation tillage systems, and in particular no-till practices, may have limited adoption by growers. Some of these region-specific problems include lower early-season soil temperatures (Kovar et al., 1992), reduced seed germination and emergence (Mock and Erbach, 1977), below-optimal plant populations, poorer weed control (Swan et al., 1994), delayed plant development and maturity (Fortin and Pierce, 1990; Fortin, 1993), increased grain moisture content (Carter and Barnett, 1987), and lower grain yield potential (Lund et al., 1993). Furthermore, relative to conventional-tillage systems, no-till grain yields and profits are often dramatically lower during the first few years of adoption (Al-Kaisi and Yin, 2004).

Tillage research trials in previous decades (i.e., approximately 1970–2000) have frequently observed that yield is less for no-till practices versus conventional tillage systems for maize grown on poorly drained, fine-textured soils (Dick et al., 1991; Vyn and Raimbult, 1993). Yet tillage system effects on yield are highly dependent upon soil type, drainage, climate/latitude, and crop rotation (Griffith et al., 1973). Research throughout the United States has shown that the yield of no-till maize grown on warmer and well drained early-season soils in rotation with another crop can be comparable to that obtained using conventional tillage practices (Kladivko et al., 1986; Dick et al., 1991; Kapusta et al., 1996; West et al., 1996).

Maize grown in rotation with another crop often yields more than maize grown after maize (Peterson and Varvel, 1989; Al-Kaisi and Yin, 2004; Wilhelm and Wortmann, 2004). Such yield improvements have been attributed to more beneficial rhizosphere microorganism communities (Turco et al., 1990); reduced pest pressure (Varvel and Peterson, 1990; Katupitiya et al., 1997); and, when grown in rotation with a legume such as soybean [*Glycine max* (L.) Merr.], greater net soil nitrogen (N) mineralization and increased residual soil N content (Gentry et al., 2001). The yield benefit of maize in a rotation varies by tillage system. Numerous studies found a greater yield improvement in a no-till system relative to other tillage systems as a result of crop rotation (e.g., Griffith et al., 1988; Lund et al., 1993).

The comparative effects of tillage systems on general aspects of maize growth and development (e.g., plant emergence date, plant height, flowering time) have been studied extensively over the past 30 years using a number of crop rotations. However, most prior studies were conducted on a short-term basis (i.e., <10 years) (e.g., Hussain et al., 1999; Karunatilake et al., 2000; Wilhelm et al., 2004), and therefore largely neglected to account for year-to-year variation in temperature and precipitation during the growing season. While a number of long-term studies (i.e., >10 years) were also performed (e.g., Linden et al., 2000; Al-Kaisi and Yin, 2004; Wilhelm and Wortmann, 2004), they principally focused on the effects of tillage and crop rotation on maize response parameters such as plant height, grain moisture content, and yield (e.g., Griffith et al., 1988; Kapusta et al., 1996; West et al., 1996).

Short- and long-term research emphasizing slower plant growth and delayed maturity in continuous maize, no-till systems (e.g., Swan et al., 1987; Griffith et al., 1988) has led to the conclusion among many growers, agronomists, and researchers that lower yields in this environment are often associated with reduced plant heights at various developmental stages (e.g., 4 and 8 weeks after planting). Shorter plants in continuous maize, no-till systems in temperate climates may result from a number of factors including greater soil residue cover and cooler, wetter early-season soil conditions, with the former causing delayed plant emergence through the physical impedance of seedling growth and the latter promoting delayed germination of seeds (Kaspar et al., 1990; Vetsch and Randall, 2002). Yet a number of studies have shown that slow early-season development (resulting in reduced plant heights) of no-till maize does not necessarily affect yield (Cox et al., 1990; Fortin and Pierce, 1990), especially in the absence of water stress.

Both early-season and mature maize plants are not always shorter in no-till systems (Kladivko et al., 1986; Imholte and Carter, 1987) since relative growth rate (Beyaert et al., 2002), moisture availability (Hussain et al., 1999), soil compaction, surface soil structure and aggregation (Kladivko et al., 1986), and fertilizer application (Kapusta et al., 1996) can additionally impact crop growth and thus plant height. Conflicting results on the effect of no-till practices on maize plant height suggest that overall plant height (whether during early development or at physiological maturity) may not be an accurate morphometric indicator or predictor of decreased yield in continuous maize, no-till systems. Given that plant-to-plant growth and developmental uniformity is strongly associated with greater yield in maize (Glenn and Daynard, 1974; Tokatlidis and Koutroubas, 2004; Andrade and Abbate, 2005; Boomsma et al., 2009), plant height variability may be a better indicator or predictor of yield loss in this environment.

The creation and maintenance of growth and developmental homogeneity within a maize stand is essential since maize is a determinate species with a relatively limited ability to adjust reproductive growth (e.g., ears $plant^{-1}$, kernel rows ear^{-1}) in response to increased resource availability (Bonaparte and Brawn, 1975). As such, when plant-to-plant variability is present within a maize stand, per-plant yield reductions among smaller, dominated (Maddonni and Otegui, 2004) plants are only partially offset by per-plant yield increases among larger, dominant individuals, thus resulting in an overall reduction in yield (Ford and Hicks, 1992; Liu et al., 2004). Plant-to-plant variability is consistently present in maize fields, with non-uniformity expressed by differences among neighboring plants in the rate of growth [e.g., when multiple plants at the same developmental stage vary in stem or ear growth rates (Pagano et al., 2007)] and/or development [e.g., when a V8 (Ritchie et al., 1996) plant is taller than a V6 plant (Liu et al., 2004)]. A majority of this by-plant variation results from cultural practices and biological phenomena as opposed to genetic variation (Glenn and Daynard, 1974; Daynard and Muldoon, 1983). Some cultural sources of plant-to-plant variability include deviations in planting depth, seed spacing, nutrient application, crop residue distribution, and plant density; while biological sources of plant-to-plant variability include variations in insect feeding, disease pressure, and soil type (Lauer and Rankin, 2004; Tokatlidis and Koutroubas, 2004; Andrade and Abbate, 2005). Continuous maize, no-till systems typically exhibit a greater number of these sources of variability relative to conventional-till maize grown in rotation with another crop (Swan et al., 1994), suggesting that plant-to-plant variability for some morpho-physiological traits may be considerably larger in no-till environments.

Both delayed and variable emergence can lead to yield loss in maize (Ford and Hicks, 1992; Liu et al., 2004). Cooler, wetter soils in continuous maize, no-till systems can delay seed germination, seedling emergence, and early root and stem development. Delayed stand establishment can lengthen the time during which seedlings are exposed to seedling blights and insect pressure (Dodd and White, 1999). This can lead to a higher proportion of weakened (i.e., dominated) plants that have to tolerate later-season stresses as well as compete with healthier (i.e., dominant) neighbors for limited resources throughout the remainder of the growing season. Emergence variability and any resulting growth and developmental non-uniformity can thus result in increased per-plant yield variability, which often lowers overall yield (Nafziger et al., 1991; Ford and Hicks, 1992; Liu et al., 2004). Since plant height uniformity is often indicative of emergence uniformity and greater yield (Glenn and Daynard, 1974; Ford and Hicks, 1992; Liu et al., 2004; Boomsma et al., 2009), further understanding the impacts of and conditions conducive for plant height variability in continuous maize, no-till systems may help identify mechanisms for yield improvement in these environments.

This study, involving 14 years of a long-term tillage and crop rotation experiment spanning more than 30 years, primarily examined the effects of crop rotation (maize–soybean and continuous maize) and tillage system (no-till and moldboard plow) on the yield, plant height, and plant height variability of a single maize variety. Due to sizeable year-to-year variation for the actual means of investigated crop parameters, actual responses for the maize–soybean, no-till; continuous maize, no-till; and continuous maize, moldboard plow treatment combinations were calculated as a percent of the accompanying actual response for the maize–soybean, moldboard plow treatment. Accordingly, we hypothesized that (i) the continuous maize, no-till environment would exhibit the smallest relative yield, lowest relative plant population, shortest relative plant height, and greatest relative plant height variability for most years of this study, (ii) relative yield of the continuous maize, no-till system would decrease when relative early-season plant height variability for this treatment increased, and (iii) relative early-season plant height variability would be a more accurate indicator or predictor of the relative yield responses of the continuous maize, no-till treatment than relative early-season plant height.

2. Materials and methods

2.1. Site description, experimental design, and treatments

A long-term tillage system and crop rotation experiment was initiated at the Purdue University Agronomy Center for Research and Education (ACRE) near West Lafayette, Indiana (40°28′07″N, 87°00′25″W) in 1975. The initial objectives of this long-term experiment were to determine the long-term crop yield potential of multiple tillage system-crop rotation combinations and identify changes in soil characteristics and crop growth related to yield differences. The soil, which had developed under prairie vegetation, was a Chalmers (fine-silty, mixed, mesic Typic Endoaquoll) silty clay loam with approximately 4.0–4.5% SOM content in the top 30 cm of the soil profile. The experimental area had less than 2% slope and was systematically tile drained at 20-m intervals.

Although the long-term tillage system and crop rotation experiment at ACRE involves four tillage systems [see West et al. (1996) for further details], only two were examined for this manuscript. No-till and moldboard plow practices were chosen since they represent opposite tillage "extremes", with the no-till system minimizing and the plow system maximizing soil disturbance (Griffith and Wollenhaupt, 1994). Therefore, for the analyses presented here, treatments consisted of two crop rotations (maize–soybean and continuous maize) and two tillage systems (no-till and moldboard plow), with these treatments defined and abbreviated as follows: maize–soybean, no-till (MB–NT); maize–soybean, moldboard plow (MB–PL); maize–maize, no-till (MM–NT); and maize–maize, moldboard plow (MM–PL).

The field experiment was arranged as a split-plot design with four blocks. Crop rotation was the whole unit treatment and tillage system was the subunit treatment. Year was considered a split-block fixed effect, making the experiment a split-plot, split-block design. Each plot was approximately 9 m wide (12 maize rows, 76-cm row spacing) and 46 m long. The same maize variety, Becks 65X (Beck's Hybrids, Atlanta, IN), was planted each year of this 14-year (1981–1994) study.

Table 1
Planting dates for all 14 years of data examined for this study (1981–1994).

Year	Planting date	Year	Planting date
1981	May 22	1988	April 26
1982	April 30	1989	April 25
1983	May 10	1990	April 26
1984	May 2	1991	May 10
1985	April 25	1992	May 5
1986	April 29	1993	May 11
1987	May 5	1994	April 26

2.2. Cultural practices

For the 14 years comprising this experiment, fall moldboard plowing was performed to a 20-cm depth, with a single disking and field cultivation to a 10-cm depth following in the spring prior to planting. No-till planting of maize was done with a single 2.5-cm bubble (1981–1989) or 2.5-cm fluted (1990–1994) coulter to cut through crop residue and loosen soil ahead of standard planter units. Maize stalks were only chopped in the spring of 1981 prior to planting. Throughout the 14-year study, maize was planted at a rate of 64,500 plants ha^{-1} for all crop rotation and tillage system treatment combinations. Planting dates ranged from April 25 to May 22 (Table 1). Planting occurred on the same day for all plots in each year of the study. For the no-till system, rows were planted upon the previous years' rows for both the maize–soybean and continuous maize rotations. Starter fertilizer was applied in a 5-cm by 5-cm band beside the seed furrow. Starter fertilizer applications included N for all years of the study, and in 1992–1994, the starter N application rate exceeded 35 kg ha^{-1}. Nitrogen was also applied as anhydrous ammonia via either a pre-plant or side-dress application at a rate of 280 kg ha^{-1} (1981–1990) or 245 kg ha^{-1} (1991–1994). Phosphorus (P), potassium (K), and lime were surface-applied as needed, often prior to primary tillage operations in the fall. Burndown herbicides were applied as necessary to control vegetation prior to planting, and pre-emergence herbicides were applied at or soon after planting. Post-emergence herbicides were only applied when pre-emergence treatments were inadequate. Some plots required additional hand-weeding to ensure weeds did not affect growth and development or depress yields. Insecticides were applied at planting for all 14 years to control western corn rootworm (Diabrotica virgifera virgifera LeConte) and black cutworm (*Agrotis ipsilon* Hufnagel). However, black cutworm damage was still significant in 1982. In 1991, a high incidence of European corn borer (*Ostrinia nubilalis* Hübner) and anthracnose stalk rot [*Colletotrichum graminicola* (Ces.) Wils.] was observed in all crop rotation–tillage system combinations. More detailed accounts of cultural practices used for all 14 years examined in this analysis are provided by West et al. (1996).

2.3. Crop and weather measurements

Plant height was measured at 4 and 8 weeks after planting as the extended leaf heights (i.e., distance from the soil surface to the uppermost extended leaf tip) of eight randomly selected plants in each plot. Plant population (8 counts $plot^{-1}$, 4 weeks after planting), grain moisture content, and final yield were also determined for each plot. Grain was harvested from the center four rows of each 12-row plot using a commercial plot harvester. Grain weight and percent moisture measurements were collected on the plot combine. Yields were corrected to 155 g kg^{-1} grain moisture content.

For the 14-year period comprising this experiment, precipitation and temperature data were recorded on a daily basis (less than 0.5 km from the study area) to examine the effects of these weather variables on multiple crop parameters. The modified growing degree day (GDD) formula was used to calculate the number of GDD accumulated during each growing season. The GDD measure of thermal time was chosen for this study since it is the most commonly used method in the United States Corn Belt for describing maize growth and development. For all analyses, precipitation and GDD data were segmented into four 4-week intervals as follows: 4 weeks pre-planting to planting (period one), planting to 4 weeks post-planting (period two), 4 weeks post-planting to 8 weeks post-planting (period three), and 8 weeks post-planting to 12 weeks post-planting (period four). Using the modified GDD formula, GDD for a given 4-week period (GDD_p) was calculated as follows:

$$GDD_p = \sum_{i=m}^{n}\left\{\left[\frac{(T_{\max}+T_{\min})}{2} - T_b\right]\right\} \quad (1)$$

where $T_{\max}$ is the daily maximum temperature (with an upper limit of 30 °C), $T_{\min}$ is the daily minimum temperature (with a lower limit of 10 °C), T_b is equal to 10 °C, m is the first day of the period, and n is the last day of the period (Dwyer et al., 1999). Precipitation and GDD accumulated during each of the four periods for each year are depicted in Fig. 1A and B.

2.4. Statistical analyses

Crop response and weather data from the long-term tillage system and crop rotation experiment at ACRE now spans more than 30 years. However, only a subset of 14 years (1981–1994) of data was chosen for the analyses presented here. These years were chosen because the same maize variety and plant population were used throughout this time period. For all analyses, block one data were omitted due to frequent flooding. Plant height measurements at 8 weeks were omitted in 1981 and 1987 due to data collection problems. Plant height variability was determined on a plot basis and expressed as the standard deviation (SD) of individual plant heights.

For analysis of variance (ANOVA) of actual data for the four treatment combinations (i.e., MB–NT, MB–PL, MM–NT, and MM–PL), the experiment was considered as a split-plot, split-block design with three blocks. Crop rotation, tillage system, and year served as the whole unit, subunit, and split-block treatments, respectively. Year was considered as a fixed effect. Analyses were performed for the even years separately from the odd years so that each set of analyses (i.e., even years and odd years) had the whole unit treatment (i.e., crop rotation) consistently assigned to the same physical plot throughout the duration of the analysis period. The whole unit error was pooled with the subunit error, and the year × whole unit error and year × subunit error were pooled. The even- and odd-year analyses were then combined into a single 12- or 14-year model since the even- and odd-year error variances were homogeneous. The SAS GLM procedure was used for ANOVA (SAS Institute, 2004). Treatment means for actual data were compared within years using Fisher's protected least significant difference (LSD) test ($P = 0.05$).

Due to sizeable year-to-year variation for the actual means of crop parameters examined (Fig. 2A–F), the MB–NT, MM–NT, and MM–PL treatment combinations were considered on a relative basis to the MB–PL treatment. More specifically, actual crop responses for the MB–NT, MM–NT, and MM–PL treatment combinations were calculated as a percent relative to the accompanying actual responses of the MB–PL treatment combination (100% = actual response for the MB–PL treatment). Treatment combinations were expressed relative to the MB–PL treatment since, among the crop rotation–tillage system combinations examined, this system typically exhibits (particularly for this study's location) (i) the highest yield (Griffith et al., 1988; West et al., 1996; Wilhelm and Wortmann, 2004), (ii) the greatest vertical spatial homogeneity for soil nutrients (i.e., reduced nutrient stratification) due to pronounced nutrient and soil acidity redistribution (Schomberg et al., 1994; Garcia et al., 2007), (iii) the least amount of surface residue cover at planting (Kladivko et al., 1986; Swan et al., 1987; Vetsch and Randall, 2000), and (iv) the most rapid and uniform early-season soil warming and drying (Fortin and Pierce, 1990; Azooz et al., 1995). Considering this study's climate and soil type, the combination of the latter three characteristics in the MB–PL environment theoretically (i) diminished the occurrence of early-season population reductions (c.f., West et al., 1996); (ii) maximized early-season growth, development, and, resultantly, overall plant height; and (iii) minimized plant-to-plant variability for germination and emergence time and early-season growth and development. For the analysis of relative data, relative values were computed for all crop parameters of interest within each block. Again, even- and odd-year analyses were conducted, with both even- and odd-year analyses combined once more because of homogeneous error variances. Similar to comparisons of actual means, relative treatment means within years were compared using Fisher's protected LSD test ($P = 0.05$).

All regression analyses were performed on relative treatment means since rather large annual variation was evident for most actual measures across 12 or 14 years (Fig. 2A–F). The SAS GLM procedure (SAS Institute, 2004) was used for all regression analyses. Regression analyses were divided into three model subsets, with the first subset involving the regression of relative

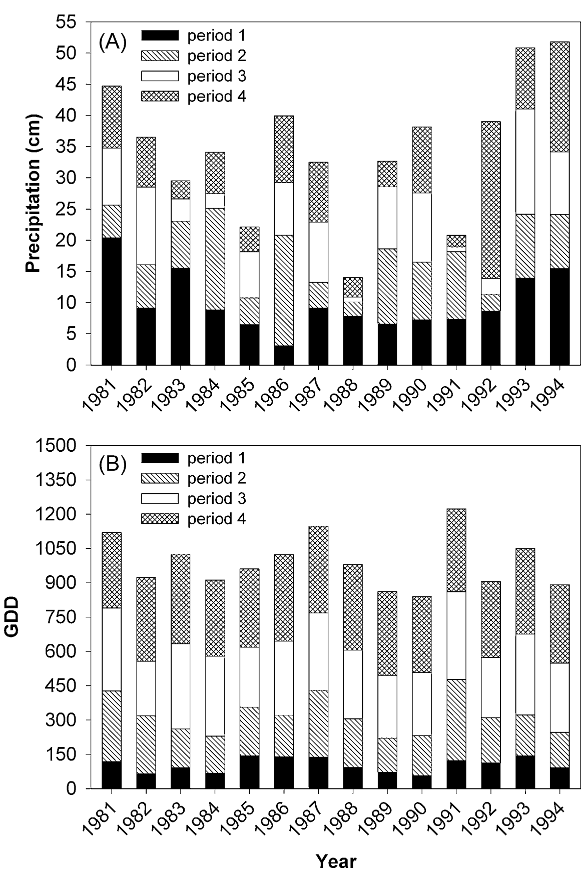

Fig. 1. Precipitation (A) and growing degree days (GDD) (B) for each year's four 4-week periods for all 14 years (1981–1994) of the study. Periods are (i) 4 weeks pre-planting to planting (period one), (ii) planting to 4 weeks post-planting (period two), (iii) 4 weeks post-planting to 8 weeks post-planting (period three), and (iv) 8 weeks post-planting to 12 weeks post-planting (period four). Each bar segment represents the total precipitation (A) or GDD (B) accumulated during that particular 4-week period. The entire bar represents the total precipitation (A) or GDD (B) accumulated during that year's entire 16-week period.

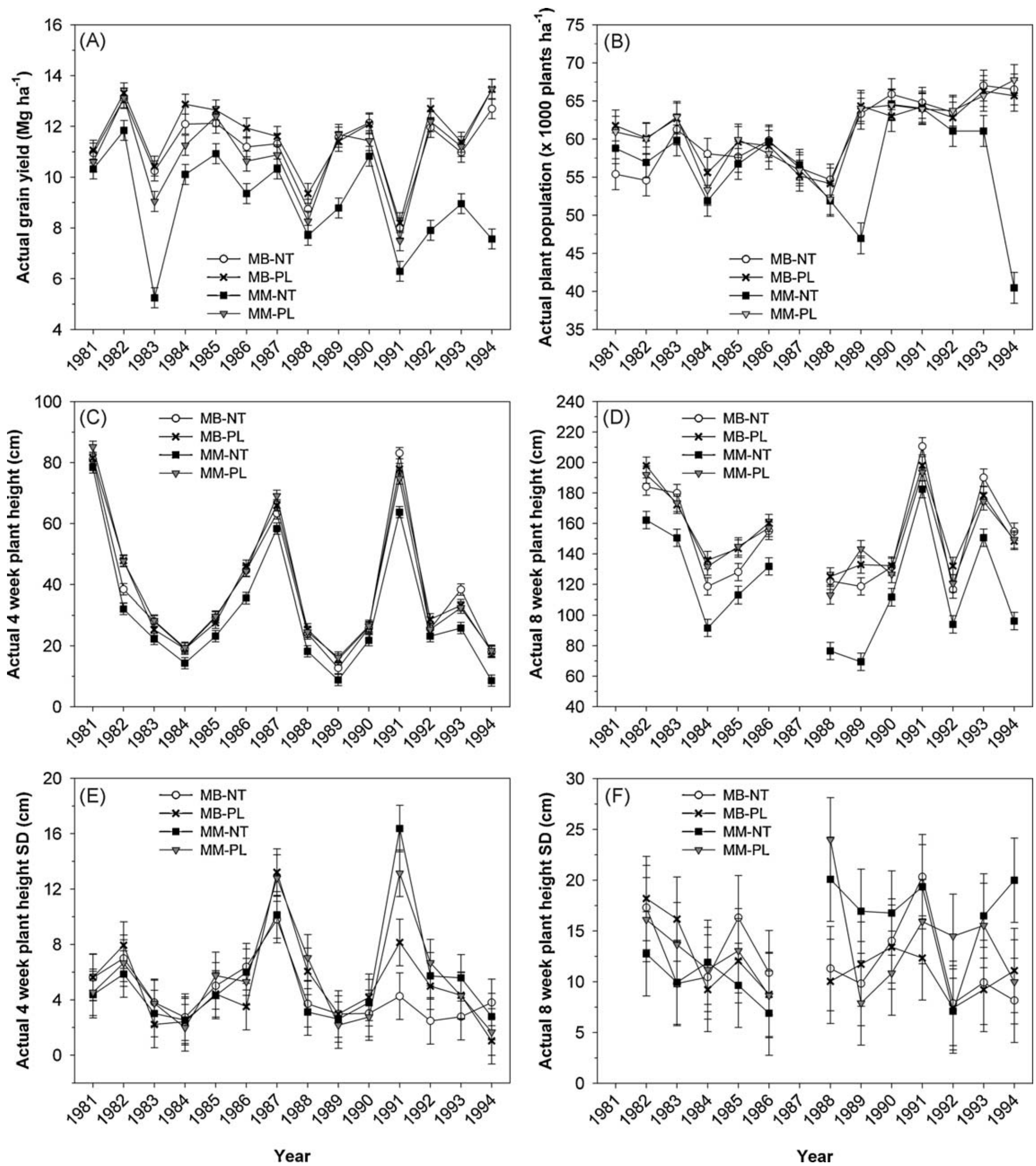

Fig. 2. Maize actual grain yield (A), actual plant population (B), actual 4 (C) and 8 (D) week plant height, and actual 4 (E) and 8 (F) week plant height standard deviation (SD) for each crop rotation–tillage system treatment for either 12 (1982–1986, 1988–1994) or 14 (1981–1994) years of the study. Crop rotation–tillage system treatments are maize–soybean, no-till (MB–NT); maize–soybean, plow (MB–PL); maize–maize, no-till (MM–NT); and maize–maize, plow (MM–PL). Error bars equal one-half of the least significant difference (LSD) at $P = 0.05$. Treatment means are significantly different within each year where error bars do not overlap.

grain yield on one independent variable, the second subset examining the regression of relative grain yield on two independent variables, and the third subset investigating the regression of relative 4-week plant height SD on two independent variables. For the first subset, independent variables considered for the model were relative 4-week plant height, relative 8-week plant height, relative 4-week plant height SD, relative 8-week plant height SD, and relative plant population. With the second subset, the first independent variable was relative 4-week plant height SD. Various precipitation and GDD totals were considered for the second independent variable. For the third subset, the independent variables considered were relative plant population, planting date (days after April 1), and various precipitation and GDD totals from periods one and two. When parameter estimates did not differ between treatment combinations for a given model, those treatment combinations were combined. Within a subset, better-fitting models had a smaller error mean square (MSE). Regression models were therefore compared for best fit by computing a two-tailed *F* value with the larger MSE as the numerator and the smaller MSE as the denominator. The regression model with a significantly smaller MSE was declared to have a better fit. Regression models for each subset that were significant and had clear agronomic value are presented in this manuscript.

3. Results and discussion

3.1. Crop rotation and tillage system effects on actual and relative crop measures

As is often the case in a long-term field study, year had a significant effect on the actual and relative measures of nearly all

Table 2
Analysis of variance (ANOVA) degrees of freedom and significance levels for maize actual grain yield, actual plant population, actual 4-week plant height and plant height standard deviation (SD), and actual 8-week plant height and plant height SD. Crop rotation–tillage system treatments are maize–soybean, no-till (MB–NT); maize–soybean, plow (MB–PL); maize–maize, no-till (MM–NT); maize–maize, plow (MM–PL).

Sources of variation	Actual grain yield		Actual plant population		Actual 4-week plant height		Actual 4-week plant height SD		Actual 8-week plant height		Actual 8-week plant height SD	
	df	Sig.	df	Sig.	df	Sig.	df	Sig.	df	Sig.	df	Sig.
Block (B)	2	NS	2	NS	2	NS	2	NS	2	NS	2	NS
Year (Y)	13	***	13	***	13	***	13	***	11	***	11	**
Error (a)	26	NS	26	NS	26	*	26	NS	22	**	22	NS
Rotation (R)	1	***	1	**	1	***	1	*	1	***	1	*
Tillage (T)	1	***	1	**	1	***	1	NS	1	***	1	NS
$R \times T$	1	**	1	*	1	***	1	NS	1	***	1	NS
Error (b)	6	**	6	*	6	NS	6	NS	6	*	6	NS
$R \times Y$	13	***	13	***	13	***	13	***	11	**	11	*
$T \times Y$	13	***	13	***	13	***	13	NS	11	***	11	NS
$R \times T \times Y$	13	***	13	***	13	*	13	NS	11	***	11	NS
Error (c)	78		78		78		78		66		66	

NS, not statistically significant at $P = 0.05$.
* Statistically significant at $P = 0.05$.
** Statistically significant at $P = 0.01$.
*** Statistically significant at $P = 0.001$.

Table 3
Analysis of variance (ANOVA) degrees of freedom and significance levels for maize relative grain yield, relative plant population, relative 4-week plant height and plant height standard deviation (SD), and relative 8-week plant height and plant height SD. Crop rotation–tillage system treatment combinations are maize–soybean, no-till (MB–NT); maize–maize, no-till (MM–NT); and maize–maize, plow (MM–PL).

Sources of variation	Relative grain yield		Relative plant population		Relative 4-week plant height		Relative 4-week plant height SD		Relative 8-week plant height		Relative 8-week plant height SD	
	df	Sig.	df	Sig.	df	Sig.	df	Sig.	df	Sig.	df	Sig.
Block (B)	2	***	2	NS	2	NS	2	NS	2	NS	2	NS
Year (Y)	13	***	13	**	13	***	13	**	11	**	11	NS
Error (a)	26	NS	26	*	26	**	26	**	22	***	22	***
Treatment combination (C)[a]	2	***	2	***	2	***	2	NS	2	***	2	NS
$C \times Y$	26	***	26	***	26	***	26	**	22	***	22	NS
Error (b)	56		56		56		56		48		48	

NS, not statistically significant at $P = 0.05$.
* Statistically significant at $P = 0.05$.
** Statistically significant at $P = 0.01$.
*** Statistically significant at $P = 0.001$.
[a] Prior to ANOVA on relative data, actual responses for the MB–NT, MM–NT, and MM–PL treatment combinations were calculated as a percent relative to the maize–soybean, plow (MB–PL) treatment combination (100% = MB–PL treatment).

crop parameters of interest (excluding relative 8-week plant height SD) (Tables 2 and 3). Large year-to-year variation for the actual measures of each crop parameter is evident in Fig. 2A–F, while less pronounced by-year variation is apparent for the relative measures in Fig. 3A–F. Expression of the MB–NT, MM–NT, and MM–PL treatment combinations relative to the MB–PL system therefore had the intended consequence of reducing the substantial by-year variability displayed by most actual measures (Figs. 2A–F and 3A–F). Annual variation for actual and relative measures likely partially resulted from by-year differences in precipitation and GDD accumulation during each of the four 4-week periods (Fig. 1A and B) (Wilhelm and Wortmann, 2004).

As with year, crop rotation had a significant effect on the actual measures of all crop parameters. While tillage system significantly affected actual yield, plant population, and 4- and 8-week plant height, it had no significant effect on actual 4- and 8-week plant height SD (Table 2). Similar to tillage effects on actual measures, the crop rotation–tillage system treatment combination had a significant influence on relative yield, relative plant population, and relative 4- and 8-week plant height, but had no significant impact on relative 4- and 8-week plant height SD (Table 3).

In 10 years of this 14-year study, the MM–NT treatment displayed significantly lower actual and relative yields than the other treatments (i.e., MB–NT, MB–PL, and MM–PL for actual yield; MB–NT and MM–PL for relative yield) (Figs. 2A and 3A). Comparatively lower yields in MM–NT environments have been widely documented in other similar studies across the midwestern United States (e.g., Moncrief et al., 1991; Pederson and Lauer, 2003). The actual and relative yields of the other three (actual yield) or two (relative yield) treatment combinations did not differ significantly for a majority of the years comprising this 14-year study (Figs. 2A and 3A). While the MB–NT and MM–PL treatments yielded at most 13% lower than the MB–PL treatment, the MM–NT treatment combination yielded up to 50% less than the MB–PL system (Fig. 3A).

Due to delayed soil warming and drying and greater disease and insect pressure, reductions in plant density are more common in a MM–NT system than in the other crop rotation–tillage system combinations considered in this study (Watkins and Boosalis, 1994; Kapusta et al., 1996; Hussain et al., 1999; Broders et al., 2007). The frequently lower and comparatively variable relative yield observed for this study's MM–NT treatment (Fig. 3A) was

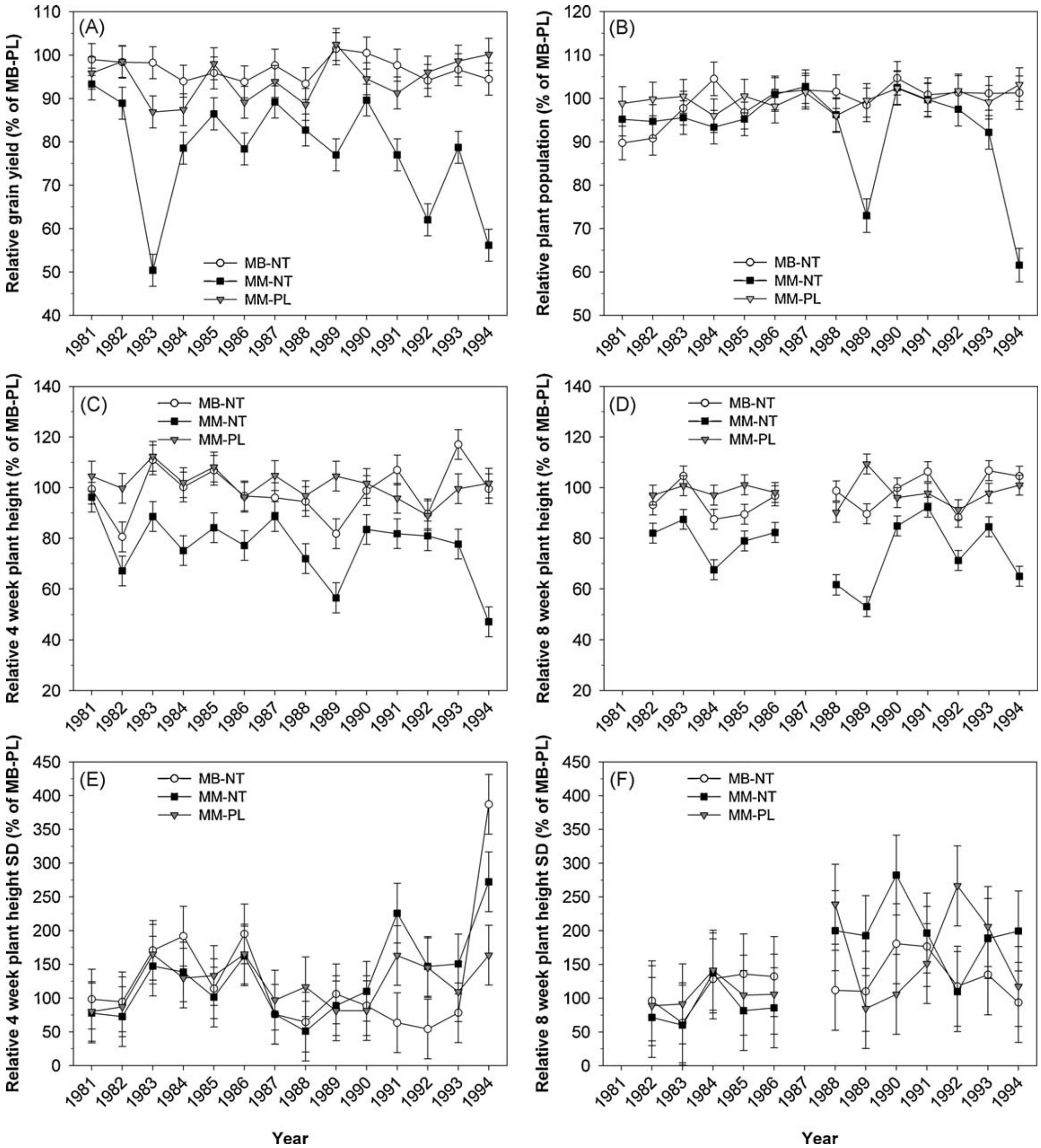

Fig. 3. Maize relative grain yield (A), relative plant population (B), relative 4 (C) and 8 (D) week plant height, and relative 4 (E) and 8 (F) week plant height standard deviation (SD) for each crop rotation–tillage system treatment combination for either 12 (1982–1986, 1988–1994) or 14 (1981–1994) years of the study. Crop rotation–tillage system treatment combinations are maize–soybean, no-till (MB–NT); maize–maize, no-till (MM–NT); and maize–maize, plow (MM–PL). For each variable, the MB–NT, MM–NT, and MM–PL treatments are expressed as a percent relative to the maize–soybean, plow (MB–PL) treatment (100% = MB–PL treatment). Error bars equal one-half of the least significant difference (LSD) at $P = 0.05$. Treatment means are significantly different within each year where error bars do not overlap.

therefore potentially due to reductions in plant density. However, although present, by-year variability for relative plant population was not as pronounced as that for relative yield for the MM–NT treatment (Fig. 3A and B). Furthermore, relative plant population for the MM–NT system was significantly less than that for the MB–NT and MM–PL treatments in only 1989 and 1994. In 1989, the relative plant population of the MM–NT treatment was roughly 30% lower than that of the MB–PL treatment, while this reduction was approximately 40% in 1994 (Fig. 3B). Actual MM–NT plant population was significantly lower than that of the other three treatments in only 1989, 1993, and 1994 (Fig. 2B). In general, years in which actual and/or relative yield was significantly lowest for the MM–NT treatment were not necessarily years in which actual and/or relative plant population was significantly lowest for this system (Figs. 2A and B and 3A and B). These results suggest that marked reductions in plant density in continuous maize, no-till environments may not fully explain the frequently lower productivity of these systems.

In addition to frequently producing lower yields than the other three (actual data) or two (relative data) crop rotation–tillage system treatments, the MM–NT system often exhibited reduced actual and relative 4- and 8-week plant heights. Both actual and relative 4-week plant heights were significantly lowest for the MM–NT treatment in 11 of 14 years (Figs. 2C and 3C), while actual and relative 8-week plant heights were significantly lowest in 11 of 12 years (Figs. 2D and 3D). Plants from the MB–NT and MM–PL treatments were at most 19% and 12% shorter than MB–PL plants at 4 and 8 weeks after planting, respectively, while MM–NT plants were up to 53% and 47% shorter than plants of the MB–PL treatment at 4 and 8 weeks after planting, respectively (Fig. 3C and

D). Such actual and relative plant height responses are generally consistent with the results of the first 12 (Griffith et al., 1988) and 20 (West et al., 1996) years of the experiment from which the 14-year dataset used for this study was extracted. In this study, the frequently shorter actual and relative plant heights of MM–NT plants at both 4 and 8 weeks after planting might initially suggest that reduced plant height may be an accurate indicator or predictor of low MM–NT yield—a contention supported by the findings of previous studies (e.g., Griffith et al., 1973; Vetsch and Randall, 2002). However, this assertion is challenged by general trends in Figs. 2A, C, and D and 3A, C, and D, which indicate that, for the MM–NT treatment, years with generally lower actual and/or relative values for 4- and/or 8-week plant height did not consistently correspond with years with comparatively lower actual and/or relative values for yield.

While actual and relative 4- and 8-week plant heights were often significantly lowest for the MM–NT treatment (Figs. 2C and D and 3C and D), in no year was actual 4-week plant height SD significantly greatest for this system, and in only a single year was actual 8-week plant height SD significantly largest for this treatment (Fig. 2E and F). Furthermore, in no year was relative plant height variability at either 4 or 8 weeks significantly greatest for the MM–NT system (Fig. 3E and F). Trends evident in Figs. 2A, E, and F and 3A, E, and F suggest that, for the MM–NT system, years with lower actual and/or relative yield(s) did not necessarily correspond with years with higher actual and/or relative 4- and/or 8-week plant height variability.

Overall, the continuous maize, no-till environment exhibited the lowest relative yield and shortest relative 4- and 8-week plant heights for many years in this study, thus lending partial support to our first hypothesis. However, in contradiction to hypothesis (i), relative plant height variability at 4 and 8 weeks after planting was rarely significantly highest for the MM–NT system and in very few years was relative plant population lowest for this treatment. Results from these analyses alone therefore suggest that early-season plant height variability (i.e., early-season growth and/or developmental non-uniformity) may not be as major a contributor to or indicator of yield loss in a MM–NT system as overall early-season plant height (i.e., overall plant growth reductions and/or developmental delays). Still, considering (i) no-till environments are more likely to exhibit non-uniform germination, emergence, and early growth and development (Vyn and Hooker, 2002), (ii) plant-to-plant variability for multiple morpho-physiological traits (including plant height) has been repeatedly associated with maize yield reductions (Glenn and Daynard, 1974; Edmeades and Daynard, 1979; Liu et al., 2004; Tokatlidis and Koutroubas, 2004), (iii) years with lower actual and/or relative yield(s) did not necessarily correspond with years with reduced actual and/or relative plant height(s), and (iv) analyses discussed thus far did not investigate direct associations between this study's measured crop parameters; a more direct examination of the relationship between relative yield and (i) relative plant height, (ii) relative early-season plant height variability, and (iii) relative plant population is both warranted and necessary.

3.2. Response of relative grain yield to relative plant height, relative plant height variability, and relative plant population

To identify which crop parameters in this study most significantly influenced relative yield for each treatment combination, single-factor regression analyses of relative yield on relative 4- and 8-week plant height, relative 4- and 8-week plant height SD, and relative plant population were performed. Statistics and parameter estimates for each of these regression models are presented in Table 4.

As shown in Table 4, the relationship between relative yield and relative measures of each of these crop parameters was highly significant for all crop rotation–tillage system combinations. Of the five parameters considered in these regression analyses, relative yield was most strongly correlated with relative 4-week plant height SD, followed by relative plant population, relative 4-week plant height, relative 8-week plant height SD, and relative 8-week plant height. Although relative 4-week plant height SD exhibited the strongest correlation with relative yield, the strength of this relationship was not statistically different from that of relative yield with relative plant population or relative 4-week plant height. Given that (i) plant-to-plant emergence, growth, and developmental variability is often associated with lower yield in maize (Liu et al., 2004; Tokatlidis and Koutroubas, 2004; Andrade and Abbate, 2005) and (ii) MM–NT systems typically exhibit a greater number of cultural (e.g., non-uniform planting depth, seed spacing, residue distribution) and biological (e.g., pest pressure) sources of plant-to-plant variability (Mock and Erbach, 1977; Broders et al., 2007), it is not entirely unexpected that reductions in

Table 4
Statistics and parameter estimates for regression models of maize relative grain yield on relative 4-week plant height standard deviation (SD), relative 4-week plant height, relative 8-week plant height SD, relative 8-week plant height, and relative plant population. Crop rotation–tillage system treatment combinations are maize–soybean, no-till (MB–NT); maize–maize, no-till (MM–NT); and maize–maize, plow (MM–PL).

Independent variable (X_1)	Model (R^2, similarity[a])	Treatment combination (C)[b]	Intercept value[c]	X_1 coefficient value
Relative 4-week plant height SD	$X_1 \times C$ (0.70[***,a])	MB–NT, MM–PL	97.74[***] (2.89)	−0.02 NS (0.02)
		MM–NT	97.74[***] (2.89)	−0.15[***] (0.02)
Relative plant population	$X_1 \times C$ (0.59[***,a])	MB–NT, MM–PL	39.78[*] (16.11)	0.56[**] (0.16)
		MM–NT	39.78[*] (16.11)	0.41[*] (0.17)
Relative 4-week plant height	$X_1 \times C$ (0.52[***,a,b])	MB–NT, MM–PL	68.95[***] (11.26)	0.26[*] (0.11)
		MM–NT	68.95[***] (11.26)	0.12 NS (0.15)
Relative 8-week plant height SD	$X_1 \times C$ (0.44[***,b])	MB–NT, MM–PL	85.46[***] (4.36)	0.06 NS (0.03)
		MM–NT	85.46[***] (4.36)	−0.05 NS (0.03)
Relative 8-week plant height	X_1 (0.42[***,b])	MB–NT, MM–PL, MM–NT	34.41[**] (11.11)	0.60[***] (0.12)

NS, not statistically significant at $P = 0.05$.
[*] Statistically significant at $P = 0.05$.
[**] Statistically significant at $P = 0.01$.
[***] Statistically significant at $P = 0.001$.
[a] Regression models followed by the same letter are not significantly different at $P = 0.05$.
[b] Prior to regression analysis, actual responses for the MB–NT, MM–NT, and MM–PL treatment combinations were calculated as a percent relative to the maize–soybean, plow (MB–PL) treatment combination (100% = MB–PL treatment).
[c] Model intercept and coefficient standard errors are enclosed in parentheses.

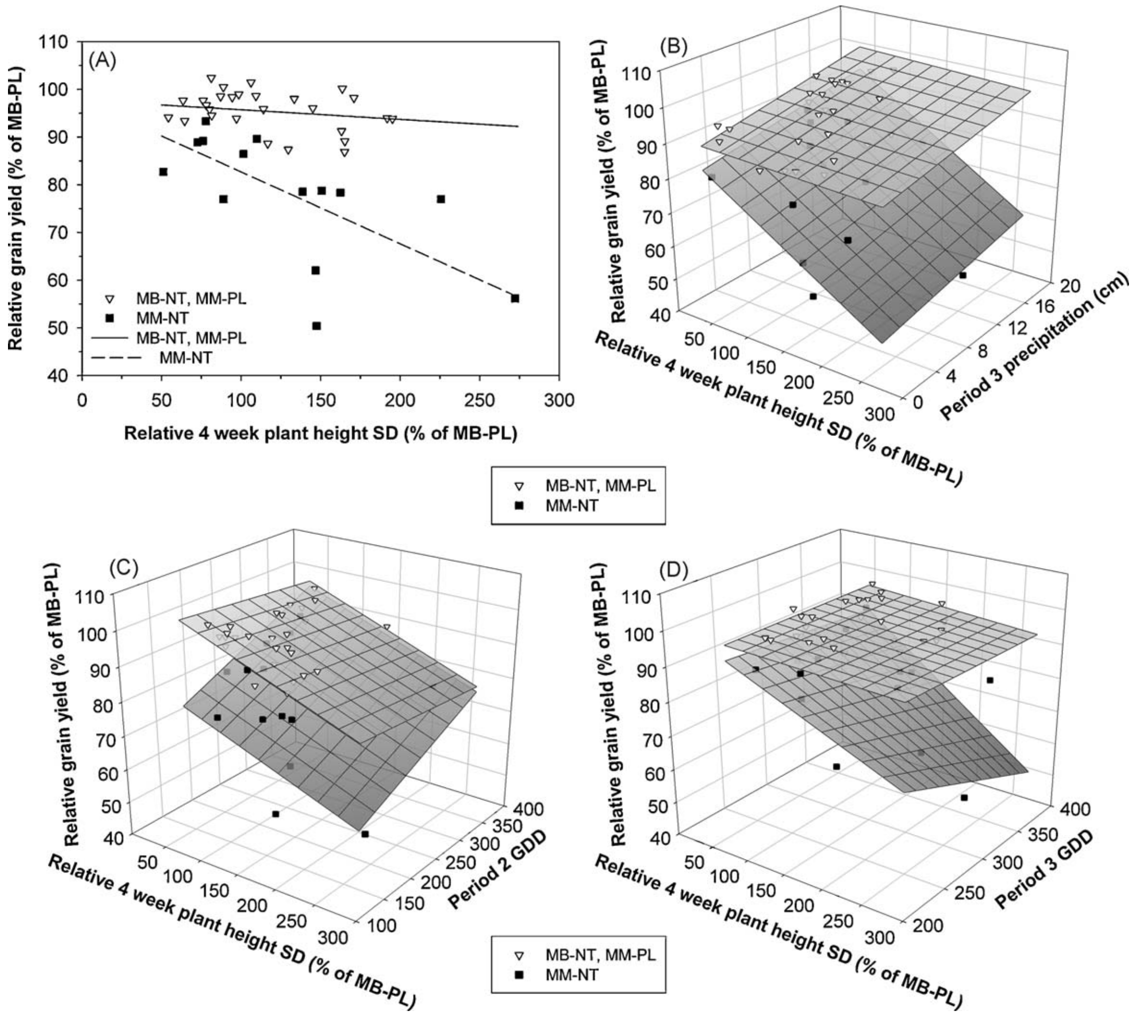

Fig. 4. Regression of relative maize grain yield on (A) relative 4-week plant height standard deviation (SD), (B) relative 4-week plant height SD and period three (i.e., 4 weeks post-planting to 8 weeks post-planting) precipitation, (C) relative 4-week plant height SD and period two (i.e., planting to 4 weeks post-planting) growing degree days (GDD), and (D) relative 4-week plant height SD and period three GDD for the maize–soybean, no-till (MB–NT); maize–maize, no-till (MM–NT); and maize–maize, plow (MM–PL) treatment combinations. Prior to regression analysis, actual responses for relative grain yield and relative 4-week plant height SD for the MB–NT, MM–NT, and MM–PL treatment combinations were calculated as a percent relative to the maize–soybean, plow (MB–PL) treatment combination (100% = MB–PL treatment). Weather variables are expressed in actual terms. Each data point represents the annual value for a particular crop rotation–tillage system combination. For regression planes, darker and lighter shading respectively indicate lower and higher values for predicted values of relative yield. Statistics and parameter estimates for regression models displayed in the figure are provided in Tables 4 and 5.

relative yield in the MM–NT system were most strongly associated with (based upon numerical comparisons of R^2 values) increases in relative early-season plant height variability.

As indicated in Table 4 and Fig. 4A, a 10% increase in relative 4-week plant height SD led to a significant decline in relative yield of 1.5% for the MM–NT treatment but had no significant effect on relative yield for the MB–NT and MM–PL treatments. Thus while greater relative plant height variability at 4 weeks after planting did not predict reduced relative yield in either the MB–NT or MM–PL system, it was strongly indicative of lower relative yield in the MM–NT system. For all treatments, an increase in relative 8-week plant height SD had no significant effect on relative yield (Table 4).

Results presented in Table 4 also indicate that a 10% increase in relative 4-week plant height led to a 2.6% higher relative yield for the MB–NT and MM–PL treatments but no significant relative yield improvement for the MM–NT system. Furthermore, a 10% increase in relative 8-week plant height led to a 6% rise in relative yield for all treatment combinations. Thus while increased relative early-season growth and development (i.e., greater relative early-season plant heights) may predict marginally higher relative yield in MB–NT and MM–PL environments, such increases may not be indicative of greater relative yield in a MM–NT system. However, greater relative plant heights later in the growing season (e.g., 8 and/or 12 weeks after planting) may indicate higher relative yield for all three crop rotation–tillage system combinations.

In this study, a 10% increase in relative plant population led to a 5.6% improvement in relative yield for the MB–NT and MM–PL treatments and a 4.1% rise in relative yield for the MM–NT treatment (Table 4). Both of these rates of relative yield increase were statistically significant, suggesting that increases in relative plant density would have led to improvements in relative yield in each of these crop rotation–tillage system combinations when plant densities were below MB–PL population (and thus likely agronomic optimal) levels. The significant, positive relationship observed between relative yield and relative plant population for this study's MB–NT, MM–NT, and MM–PL systems is in general agreement with previous studies which, through the analysis of actual data values, found a positive linear (Ahmadi et al., 1993), curvilinear (Hashemi et al., 2005), or quadratic (Tollenaar, 1992) response between yield and plant density. In each of these studies, yield generally decreased when plant density fell below a variety's agronomic optimal plant density.

Overall, results from these regression analyses generally support our second and third hypotheses in that (i) relative yield of the continuous maize, no-till system decreased when relative early-season (i.e., 4-week) plant height variability for this treatment increased and (ii) relative early-season plant height variability was a more accurate indicator or predictor of the relative yield response of the continuous maize, no-till treatment than relative early-season plant height.

3.3. Response of relative grain yield to relative plant height variability and various weather parameters

In order to determine the weather parameters which, when combined with 4-week plant height variability, most significantly impacted relative yield, we performed multi-factor regression analyses of relative yield on relative 4-week plant height SD and various precipitation and GDD totals. Relationships that were statistically significant and exhibited clear agronomic value are displayed in Fig. 4B–D. Accompanying statistics and parameter estimates for each of these regression models are presented in Table 5.

Regression of relative yield on relative 4-week plant height SD and period three (i.e., 4 weeks post-planting to 8 weeks post-planting) precipitation indicated that for the MM–NT treatment relative yield fell when relative 4-week plant height SD increased and period three precipitation decreased (Fig. 4B, Table 5). Such results suggest that commonly low relative yields for the MM–NT treatment (Fig. 3A) may have resulted from a scenario in which the establishment of early-season by-plant variability was followed by dry soil conditions that intensified intra-specific competition for limited soil moisture. Such competition not only likely lowered overall canopy-level productivity but also potentially limited the compensatory growth of weakened or dominated plants during subsequent growth and development (Daynard and Muldoon, 1983; Maddonni and Otegui, 2004).

Regression of relative yield on relative 4-week plant height SD and period two (i.e., planting to 4 weeks post-planting) GDD indicated that for the MM–NT treatment relative yield generally fell when relative 4-week plant height SD increased and period two GDD declined (Fig. 4C, Table 5). When early-season GDD accumulation is relatively low, soil warming and drying is often both slow and spatially variable in a MM–NT environment due to copious, non-uniform surface residue cover. As a result, germination, emergence, growth, and development are often delayed at the population level and more variable at the per-plant level, resulting in reductions in overall yield (Gupta et al., 1983; Swan et al., 1994; Azooz et al., 1995; Linden et al., 2000; Wilhelm and Wortmann, 2004).

As shown in Fig. 4D, regression of relative yield on relative 4-week plant height SD and period three (i.e., 4 weeks post-planting to 8 weeks post-planting) GDD indicated that for the MM–NT treatment relative yield fell when both relative 4-week plant height SD and period three GDD increased. As a result of the significant response to the product of relative 4-week plant height SD and period three GDD for the MM–NT system (Table 5), the rate of decrease in relative yield increased as the values for both independent variables increased (Fig. 4D). We propose that when the occurrence of substantial relative 4-week plant height variability was followed by high GDD accumulation 4–8 weeks after planting for the MM–NT system, later-emerging, dominated plants potentially became increasingly disadvantaged relative to their earlier-emerging, dominant neighbors due to symmetric and/or asymmetric intra-specific competition for light and soil resources (Weiner and Thomas, 1986; Casper and Jackson, 1997; Park et al., 2003). During period three, dominant plants may have begun rapid stem elongation [i.e., V10 onwards (Ritchie et al., 1996)] before their dominated neighbors, resulting in further shading of and incidental growth reductions in markedly shorter plants.

3.4. Response of relative plant height variability to planting date and various weather parameters

Multi-factor regression analyses of relative 4-week plant height SD on planting date and various precipitation and GDD totals were performed to further understand how these parameters impacted relative 4-week plant height variability during this 14-year study. Relationships that were statistically significant and exhibited clear

Table 5
Statistics and parameter estimates for regression models of maize relative grain yield on combinations of relative 4-week plant height standard deviation (SD) and period three (i.e., 4 weeks post-planting to 8 weeks post-planting) precipitation, period two (i.e., planting to 4 weeks post-planting) growing degree days (GDD), and period three GDD. Crop rotation–tillage system treatment combinations are maize–soybean, no-till (MB–NT); maize–maize, no-till (MM–NT); and maize–maize, plow (MM–PL).

Independent variable 1 (X_1)	Independent variable 2 (X_2)	Model (R^2, similarity[a])	Treatment combination (C)[b]	Intercept value[c]	Model term	Coefficient value	Model term	Coefficient value
Relative 4-week plant height SD	Period 3 precipitation	$X_1 \times C\ X_2$ (0.74***,a)	MB–NT, MM–PL	92.71*** (3.44)	$X_1 \times C$	−0.01 NS (0.02)	X_2	0.51* (0.21)
			MM–NT	92.71*** (3.44)	$X_1 \times C$	−0.14*** (0.02)	X_2	0.51* (0.21)
Relative 4-week plant height SD	Period 2 GDD	$C\ X_1\ X_2 \times C$ (0.73***,a)	MB–NT, MM–PL	109.59*** (5.77)	X_1	−0.09*** (0.02)	$X_2 \times C$	−0.01 NS (0.01)
			MM–NT	71.31*** (7.15)	X_1	−0.09*** (0.02)	$X_2 \times C$	0.05** (0.02)
Relative 4-week plant height SD	Period 3 GDD	$X_1 \times X_2 \times C$ (0.66***,a)	MB–NT, MM–PL	96.52*** (2.67)	$X_1 \times X_2 \times C$	−0.00002 NS (0.00004)		
			MM–NT	96.52*** (2.67)	$X_1 \times X_2 \times C$	−0.00024*** (0.00004)		

NS, not statistically significant at $P = 0.05$.
* Statistically significant at $P = 0.05$.
** Statistically significant at $P = 0.01$.
*** Statistically significant at $P = 0.001$.
[a] Regression models followed by the same letter are not significantly different at $P = 0.05$.
[b] Prior to regression analysis, actual responses for the MB–NT, MM–NT, and MM–PL treatment combinations were calculated as a percent relative to the maize–soybean, plow (MB–PL) treatment combination (100% = MB–PL treatment).
[c] Model intercept and coefficient standard errors are enclosed in parentheses.

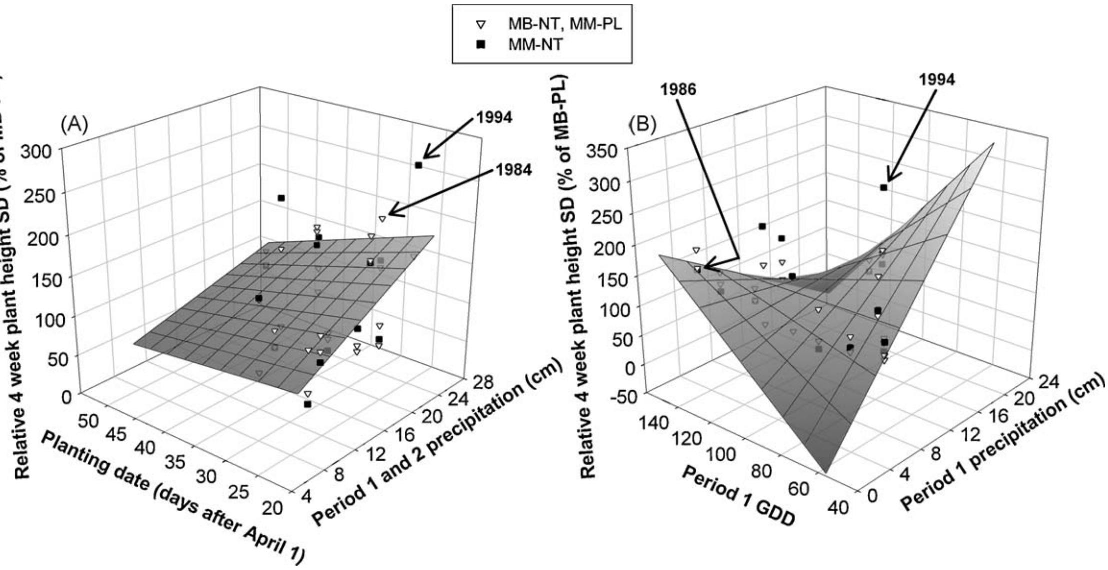

Fig. 5. Regression of maize relative 4-week plant height standard deviation (SD) on (A) period one (i.e., 4 weeks pre-planting to planting) and two (i.e., planting to 4 weeks post-planting) precipitation and planting date (days after April 1) and (B) period one precipitation and period one growing degree days (GDD) for the maize–soybean, no-till (MB–NT); maize–maize, no-till (MM–NT); and maize–maize, plow (MM–PL) treatment combinations. Prior to regression analysis, actual responses for relative 4-week plant height SD for the MB–NT, MM–NT, and MM–PL treatment combinations were calculated as a percent relative to the maize–soybean, plow (MB–PL) treatment combination (100% = MB–PL treatment). Weather variables are expressed in actual terms. Each data point represents the annual value for a particular crop rotation–tillage system treatment combination. For regression planes, darker and lighter shading respectively indicate lower and higher values for predicted values of relative 4-week plant height SD. Statistics and parameter estimates for regression models displayed in the figure are provided in Table 6. The purpose of designating particular data points with arrows and accompanying years is discussed in the text (Section 3.4).

Table 6
Statistics and parameter estimates for regression models of maize relative 4-week plant height standard deviation (SD) on combinations of planting date (days after April 1) and/or various precipitation and growing degree day (GDD) totals. Crop rotation–tillage system treatment combinations examined during regression analysis were maize–soybean, no-till (MB–NT); maize–maize, no-till (MM–NT); and maize–maize, plow (MM–PL). No treatment combination had a significant effect on the presented regression models.

Independent variable 1 (X_1)	Independent variable 2 (X_2)	Model[a] (R^2, similarity[b])	Intercept value[c]	Model term	Coefficient value	Model term	Coefficient value	Model term	Coefficient value
Planting date	Period 1[d] and 2[e] precipitation	X_2 $X_1 \times X_2$ (0.25**,a)	32.73 NS (26.36)			X_2	8.33** (2.45)	$X_1 \times X_2$	−0.11* (0.05)
Period 1 precipitation	Period 1 GDD	X_1 X_2 $X_1 \times X_2$ (0.32**,a)	−198.08* (78.48)	X_1	35.87*** (8.80)	X_2	1.53*** (0.37)	$X_1 \times X_2$	−0.17*** (0.04)

NS, not statistically significant at $P = 0.05$.
* Statistically significant at $P = 0.05$.
** Statistically significant at $P = 0.01$.
*** Statistically significant at $P = 0.001$.
[a] Prior to regression analysis, actual responses for the MB–NT, MM–NT, and MM–PL treatment combinations were calculated as a percent relative to the maize–soybean, plow (MB–PL) treatment combination (100% = MB–PL treatment).
[b] Regression models followed by the same letter are not significantly different at $P = 0.05$.
[c] Model intercept and coefficient standard errors are enclosed in parentheses.
[d] 4 Weeks pre-planting to planting.
[e] Planting to 4 weeks post-planting.

agronomic value are displayed in Fig. 5A and B. Accompanying statistics and parameter estimates for each of these regression models are presented in Table 6.

Regression of relative 4 plant week plant height SD on planting date (expressed as days after April 1) and period one (i.e., 4 weeks pre-planting to planting) and two (i.e., planting to 4 weeks post-planting) cumulative precipitation indicated that relative 4-week plant height variability rose with earlier planting and greater period one and two rainfall. Furthermore, greater cumulative precipitation from 4 weeks before until 4 weeks after planting increased relative 4-week plant height variability more for earlier planting dates than for later ones (Fig. 5A, Table 6). As indicated in Table 6, the regression relationship displayed in Fig. 5A was similar for all treatments. The increase in relative 4-week plant height variability resulting from earlier planting and greater period one and two precipitation may have been caused by (i) planting into cool, moist soils and (ii) delays in soil warming and drying (Vyn and Hooker, 2002). Under such soil conditions, germination and emergence were likely both delayed and non-uniform. Such delays potentially lengthened the exposure time of some seeds and seedlings to a variety of disease inocula (e.g., *Pythium* spp., *Fusarium* spp., *Rhizoctonia* spp.) (Colhoun, 1973; Dodd and White, 1999; Broders et al., 2007), potentially resulting in reduced seedling vigor, greater seedling death, and pronounced population reductions. These conditions also likely increased the proportion of weakened plants that were both shorter at 4 weeks after planting and less able to tolerate later-season intra-specific competition and/or abiotic stress. In this study, years with the highest relative 4-week plant height SD for each treatment occasionally corresponded to years with comparatively higher period one and two precipitation, relatively lower period one and two GDD, and generally reduced actual plant populations (e.g., 1984 and 1994) [Figs. 1A and B, 2B, and 5A (see highlighted years)]. Given the breeding era of this study's variety (commercially released in

1981), the use of less effective fungicide seed treatments during this study's time period (relative to today's products), and these periodic population reductions, disease contributions to emergence and resulting plant height variability in some years of this study were possible. Although cool, moist soil conditions; slow, variable soil warming and drying; and relatively high seed and seedling disease incidence are generally more common in MM–NT than MB–NT or MM–PL environments (Gupta et al., 1983; Imholte and Carter, 1987; Kaspar et al., 1990; Karunatilake et al., 2000; Broders et al., 2007), results in Figs. 2B and 5A suggest that these conditions were likely at least partially responsible for the significant regression relationship observed (Fig. 5A) for the MB–NT and MM–PL systems. Still, other sources of emergence variability and resulting plant height non-uniformity may have been important factors in these environments. Unfortunately, without further soil and crop measurements, they cannot be conclusively identified from this dataset.

Regression of relative 4-week plant height SD on both period one (i.e., 4 weeks pre-planting to planting) precipitation and period one GDD indicated that relative 4-week plant height SD rose when pre-plant weather conditions were cool and moist or warm and dry. However, relative 4-week plant height variability declined when pre-plant weather conditions were increasingly cool and dry or warm and moist (Fig. 5B, Table 6). As indicated in Table 6, the regression relationship displayed in Fig. 5B was similar for all treatments. Similar to results discussed earlier (e.g., Figs. 4C and 5A), exceptionally cool, wet weather during the pre-plant period likely encouraged high disease incidence; delayed, non-uniform germination; and slow, uneven emergence in MB–NT, MM–PL, and, in particular, MM–NT systems (Colhoun, 1973; Sumner et al., 1981; Imholte and Carter, 1987; Dodd and White, 1999). Variable germination and emergence were also likely promoted by warm, dry pre-plant weather patterns that led to dry seedbed conditions at planting in which a portion of the seed potentially germinated and emerged normally, while the rest remained inactive until sufficient rain fell to enable germination and subsequent emergence (Nafziger et al., 1991).

While continuous maize, no-till environments often exhibit high early-season soil moisture levels that can be detrimental to germination, emergence, and early growth in some climates (Fortin, 1993; Karunatilake et al., 2000; Vyn and Hooker, 2002), these same soil conditions may improve the timeliness and by-plant uniformity of germination and emergence when pre-plant weather is relatively dry and warm. For example, relative 4-week plant height variability was lower for the MM–NT treatment when period one weather was relatively dry and warm (e.g., 1986) than when it was wet and cool (e.g., 1994) [Figs. 1A and B, 3E and 5B (see highlighted years)]. As suggested in Fig. 5B, warm and wet pre-plant weather conditions likely led to seedbed environments in the MB–NT, MM–NT, and MM–PL systems that promoted rapid and uniform germination, emergence, and early seedling growth relative to the MB–PL treatment, therefore resulting in plants of generally uniform relative 4-week plant height (Vyn and Hooker, 2002).

4. Summary and conclusions

Substantial crop residue cover and cool, moist early-season soil conditions are common characteristics of MM–NT systems that often delay seed germination, seedling emergence, and early root and stem development and prolong seed and seedling exposure to disease inocula. Growers and agronomists commonly associate these early-season MM–NT phenomena with reduced early- and mid-season plant heights, delayed development, sub-optimal plant populations, and, consequently, lower grain production. The findings of this study lend some support to these associations, as in numerous years the MM–NT system produced lower actual and relative yields and exhibited shorter actual and relative 4- and 8-week plant heights compared to the other crop rotation–tillage system combinations. Both actual and relative plant height variability at 4 and 8 weeks after planting were rarely greater for the MM–NT treatment for most years of this study, and in only a few years were actual and/or relative plant density lower for this system.

However, regression analyses revealed that a decline in relative MM–NT yield was significantly associated with an increase in relative 4-week plant height variability. Decreases in relative 8-week plant height and relative plant density were also significantly associated with lower relative yield in the MM–NT system, but the strength of these associations was less than that between relative 4-week plant height variability and relative yield. While this is the first study (to the best of our knowledge) to identify early-season relative plant height variability as a strong indicator of (or agronomic explanation for) relative yield reductions in a MM–NT environment, this finding is not entirely unexpected given this system's early-season characteristics at and below the soil surface. In this study, weather conditions that contributed to overall yield loss in the MM–NT environment potentially did so by (i) encouraging the establishment of per-plant variability through the delayed emergence of some seedlings and (ii) intensifying early- and later-season intra-specific competition between dominant and dominated plants. The former was potentially promoted by cool and moist or warm and dry pre-plant weather conditions. The latter may have been encouraged by low precipitation and/or high temperatures during the period of rapid stem elongation.

Based upon this study's findings, we propose that while MM–NT systems should be managed so as to limit reductions in plant density and overall delays in growth and development, focus should also be placed on minimizing the establishment and subsequent intensification of plant-to-plant variability in these environments. Some ways by which this may be accomplished include (i) planting at a later date or when soils are warmer and drier, (ii) spreading crop residue uniformly at harvest, (iii) using seed firmers and tined row cleaners in high-residue seedbeds, (iv) providing adequate starter and total N, (v) selecting disease-resistant hybrids and effective fungicide seed treatments to enhance seedling vigor, and (vi) implementing controlled traffic programs (Watkins and Boosalis, 1994; Vetsch and Randall, 2000; Boomsma and Vyn, 2007). Future research efforts should seek to further understand the soil and weather conditions that promote the onset and escalation of plant-to-plant variability in a MM–NT system and attempt to identify cropping practices that minimize plant-to-plant variability while promoting grower profitability and environmental sustainability.

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