Field Crops Research 302 (2023) 109090

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Plant emergence and maize (*Zea mays* L.) yield across multiple farmers' fields

S. Albarenque [a,b], B. Basso [c,d,*], O. Davidson [e], B. Maestrini [f], R. Melchiori [b]

[a] *Department of Plant, Soil and Microbial Sciences, Michigan State University, East Lansing, MI, USA*
[b] *Instituto Nacional de Tecnología Agropecuaria EEA Paraná, Paraná, Entre Ríos, Argentina*
[c] *Department of Earth and Environmental Sciences, Michigan State University, East Lansing, MI, USA*
[d] *W.K. Kellogg Biological Station, Michigan State University, Hickory Corners, MI, USA*
[e] *Environmental Protection Agency, Chicago, IL, USA*
[f] *Agrosystems Research Group, Wageningen University & Research, Wageningen, the Netherlands*

ARTICLE INFO

Keywords:
Plant emergence
Maize yield
Kernel number
Kernel weight
Spacing
Yield stability zones

ABSTRACT

Context: Uneven crop stands result from natural variation in emergence time that is related to soil moisture and temperature, and variation of within-row plant-to-plant distance caused during planting operations. Understanding the effect of the spatial and temporal variation of plant emergence on crop yield can help farmers make improved management decisions about planting.
Objective: The objectives of this work were to i) compare the timing of maize plant emergence across and within sub-field yield stability zones, ii) evaluate the impact of delayed emergence on crop yield and yield components by yield stability zone, and iii) compare the effect of spatial and temporal variability of plant emergence on crop yield and yield components.
Methods: Ten experiments were conducted in farmers' maize fields in Springport (Michigan, US), Portland (Michigan, US), and Parana (Entre Rios, Argentina). Several years of yield monitored data for each field were used to delimitate yield stability zones (YSZ). Individual plant emergence was recorded daily, across yield stability zones. Emerged plants were tagged and the distance between plants within the row was recorded and used to calculate plant growing space (cm^2 plant^{-1}), and to classify them within plant stand as uniform, double or skips. Tagged plants were hand harvested to analyze the individual plant yield, number and weight of grains, and total crop yield.
Results: Individual plant emergence time ranged from 3 to 31 days after planting (DAP). The variation in timing of plant emergence had a greater impact than the variation of within-row plant spacing on crop yield and yield components. In general, the impact was larger in stable low yield areas. On average, plant yield was reduced by 7 %, grain number by 6 %, and final crop yield by 8.5 % per day of emergence delay after planting. The greater variation in the days of emergence delay when compared to within-row plant spacing variation can be related to the small overall spatial variability within the rows.
Conclusions: Plant emergence temporal variability had a higher impact than within-row plant spatial variability on crop yield and its components. The decrease in maize yield caused by the delay in emergence was not statistically related to yield stability zones. However, a trend of a more negative impact of delayed emergence in the low yield stability zones was observed.
Implications: Understanding factors affecting the spatial and temporal plant emergence patterns of crops can help farmers optimize their planting operation and may help them with decisions on using more precise and tailored inputs (such as seed rate and nitrogen fertilizer) on different sub-field yield stability zones. Incorporating emergence data and information into crop models will also help improve yield simulation results.

Abbreviations: DAP, days after planting; GS, plant growing space (cm^2 plant^{-1}); HS, high stable yield stability zone; LS, low stable yield stability zone; MS, medium stable yield stability zone; UN, unstable yield stability zone; YSZ, yield stability zone.

* Corresponding author at: Department of Earth and Environmental Sciences, Michigan State University, East Lansing, MI, USA.
E-mail address: basso@msu.edu (B. Basso).

https://doi.org/10.1016/j.fcr.2023.109090
Received 22 April 2023; Received in revised form 25 July 2023; Accepted 7 August 2023

Table 1
Experimental site, year-field, soil class, and management.

Site	Year-Field	Predominant Soil Taxonomic class	Tillage System†	Plant density (plants ha^{-1})	Row spacing (cm)	Field Size (ha)	Relative maturity	Planting date	Silking date
Springport	2016–222	Fine-loamy, mixed, active, mesic Typic Hapludalfs	NT	74131	76.2	35	96	21-May	26-Jul
	2017–222	Fine-loamy, mixed, active, mesic Typic Hapludalfs	NT	74131	76.2	35	96	25-May	30-Jul
	2018–105	Fine-loamy, mixed, active, mesic Typic Hapludalfs	NT	74131	76.2	106	96	4-Jun	5-Aug
	2019–304	Very-fine, mixed, active, frigid Aquic Glossudalfs	NT	74131	76.2	32	95	8-Jun	8-Aug
	2020–308	Very-fine, mixed, active, frigid Aquic Glossudalfs	NT	74131	76.2	29	102	11-May	23-Jul
	2021–210	Very-fine, mixed, active, frigid Aquic Glossudalfs	NT	74131	76.2	150	95	15-May	27-Jul
Portland	2017-JS1	Coarse-loamy, mixed, semiactive, nonacid, frigid Mollic Endoaquepts	C	93899	50.8	34	95	18-May	24-Jul
	2018-NC12	Coarse-loamy, mixed, semiactive, nonacid, frigid Mollic Endoaquepts	C	93899	50.8	28	95	1-May	17-Jul
	2019-MG1	Fine, mixed, active, mesic Haplic Glossudalfs	C	93899	50.8	25	104	8-Jun	12-Aug
Parana	2020–11	Fine, montmorillonitic, thermic Vertic Argiudolls	NT	70000	52	17	122	29-Dec	5-Mar

†*NT:* no-till, *C:* conventional

1. Introduction

Uniform crop stands can outyield non-uniform stands when the growing conditions and management are favorable (Andrade and Abbate, 2005; Lawles et al., 2012). Unevenness might result from natural variation in emergence that is mainly related to soil moisture and soil temperature variability (Andrade and Abbate, 2005). Early emerging plants have an advantage in obtaining resources when compared to those emerging later. They become taller have a better-developed root system earlier in the growing season (Liu et al., 2004a), which can lead to higher yields. There is evidence of an asymmetric competition for light, as the initially suppressed plants (dominated) exhibited the highest level of responsiveness to thinning (Pagano and Maddonni, 2007). The variable distance between emergent and growing plants is mainly caused during planting operations (Liu et al., 2004b) and can contribute to plant stand variability (emerged plants m^{-2}) (Daynard and Muldoon, 1983). Heterogeneity in the distance between plants may cause variable yield loss associated with very closely placed plants that is not compensated for by the additional yield of plants located in gaps, thereby decreasing overall yield (Novak and Ransom, 2018).

The literature is consistent in reporting the negative effect of delayed emergence on crop yield (Andrade and Abbate, 2005; Liu et al., 2004a, 2004b; Nafziger et al., 1991; Tollenaar and Wu, 1999). Carter et al. (1990) planted maize at several dates to simulate delayed emergence and reported between 10 % and 22 % yield reduction in plants with a 21-day delay in the emergence, noting that late emerged plants could not compete with early emerged plants for resources. Nafziger et al. (1991), studied several hybrids in different environments in Illinois and Wisconsin, and reported a 0.69 Mg ha^{-1} yield loss when emergence was delayed between 10 and 12 days, and up to 1.44 Mg ha^{-1} with 22-day delays. Moreover, grain yield has been shown to be lower in uneven emerged stands with increased density, where early emerging plants produced more grain per plant than late emerging plants (Ford and Hicks, 1992). Recently, Nemergut et al. (2021) reported per-plant yield reductions of 5.25 % per day of delay in emergence when the plants emerged nearly 7 days after planting.

Unlike emergence delay, the impact of within-row plant spatial variability has shown contrasting results. Liu et al. (2004c), evaluated different standard deviations of within-row plant spacing and reported no significant effect on yield, leaf number, plant height, leaf area index, and harvest index. Similarly, Lauer and Rankin (2004) reported that grain yield was rarely affected by plant spacing variability and that maize plants can compensate for plant spacing variability when plant density is adequate. In contrast, other authors observed significant yield decreases ranging from 83 to 128 kg ha^{-1} for every 10 % increase in the plant spacing variation coefficient, mainly related to grain number decreases (Sangoi et al., 2012; Kolling et al., 2019). Contrasting results in within-row spatial variability might be related to variations in the procedures used to simulate plant spacing variability, which range from the more basic hand planting and plant thinning once the plants emerged, to the more complex, including herbicide use in Roundup-ready and traditional seed mixtures (Kolling et al., 2019; Liu et al., 2004c; Pommel et al., 2002).

While these and other studies have added to our knowledge of emergence delay and spatial variability of planting, the conditions under which they were performed, the methods used to generate spatial and temporal variability, and the objectives of the studies still leave a number of further questions to be investigated. We are not aware of any studies that have been performed in fields under commercial production conditions; a more complex scenario where many additional factors and interactions can affect yield. Similarly, while prior studies have analyzed emergence variation and within-row spatial variation, separately or together, the majority have been manipulative, i.e., the variation in emergence was obtained with different specified planting dates and the variation of within-row planting spacing through post emergence

Fig. 1. Illustration of a plot setting in a) field 2019–304 no-till before emergence, b) field 2019–304 after emergence, and c) field 2021–210, no-till and cover crop, after emergence. The number in the white stakes indicates emergence in days after planting, from left to right: 23, 4, 11, and 6. Fields 2019–304 and 2021–210 were in Springport (MI) (42.3471°N, 84.7097°W).

thinning. Likewise, while studies have explored the relationships between delayed emergence and individual plant yield, height, and crop growth rate, they have not explored the effect on yield components. Therefore, questions that remain unanswered include: Is emergence delay related to the spatial variability of the soil and prior yields? Which yield component is more affected by emergence delay (kernel number vs kernel weight)? Our study aims to answer these questions. Thus, in this study, we i) compared the delay in plant emergence across sub-field yield stability zones under commercial farm conditions; ii) evaluate the impact of emergence delay on crop yield and yield components by yield stability zones, and iii) compare the effect of spatial and temporal variation of plants emergence on maize crop yield and yield components.

2. Methods

2.1. Sites description and general characteristics

Field experiments were conducted in nine commercial maize producers' fields located in Portland (MI) (42.8971°N, 84.9776°W) and Springport (MI) (42.3471°N, 84.7097°W), and in one production field located at the National Institute of Agricultural Technology Research Station in Parana (INTA EEA Parana, Argentina) (32.2336°S, 60.5338°W) (Table 1). According to the Köppen climate classification the Michigan study areas are characterized as cold, without dry season, hot summer (Dfb) with a mean average daily temperature of 7.9 °C and precipitation averaging 895 mm annually in the, whereas the Parana study area is characterized as temperate, without dry season, hot summer (Cfa) with an average daily temperature of 18.9 °C and precipitation averaging 1101 mm annually. Fields varied in soil properties and management practices, such as tillage system, plant density, row spacing, hybrid relative maturity, and planting date (Table 1). The Springport fields were planted with a White planter 9924VE, Portland

Table 2

Precipitation (mm) during 7 periods before planting and after planting, total precipitation accumulated during the crop growing season (May/October for Springport and Portland, and December/April for Parana), and temperature (°C) during the emergence period and during the crop growing season.

Site	Year-Field	Cumulative precipitation (mm)									Temperature (°C)			
		-4wk†	-3wk§	-2wk‡	-1wk¶	+ 1wkǂ	+ 2wk£	R1 ± 2wk#	Total in-season	Total Historical	Em in-season	Em Historical avg	Avg in-season	Historical Average
Springport	2016–222	63	35	25	0	2	12	58	414	447	18.0	15.5	20.0	17.7
	2017–222	110	64	63	55	6	6	32	238	447	17.0	15.5	19.0	17.7
	2018–105	138	59	34	26	16	16	84	407	447	19.5	15.5	20.5	17.7
	2019–304	94	71	49	20	88	47	19	420	446	16.5	15.5	19.3	17.7
	2020–308	57	43	32	10	63	103	84	418	446	17.5	15.5	19.3	17.7
	2021–210	18	15	10	1	3	43	154	607	446	18.0	15.5	19.9	17.7
Portland	2017-JS1	75	50	0	0	0	0	82	294	454	16.6	16.7	18.4	18.5
	2018-NC12	90	67	6	2	19	64	44	425	454	18.8	16.7	19.9	18.5
	2019-MG1	103	66	52	23	40	89	44	576	454	15.8	16.7	18.6	18.5
Parana	2020–11	115	58	24	1	2	28	91	680	541	23.5	23.9	23.0	22.9

[†] -4wk: four weeks before planting, [§] -3wk: three weeks before planting, [‡] -2wk: two weeks before planting, [¶] -1wk: one week before planting, ǂ+ 1wk: one week after planting, [£] + 2wk: two weeks after planting, [#] R1 ± 2wk: 30-d period around flowering. In-season: cumulative precipitation and average temperature during the emergence period (Em in-season, May-June for Springport and Portland, and December-January for Parana) and the growing season (Total in-season and Avg in-season, May-October, and December-April, for Michigan and Parana sites, respectively. Historical average: 30-Year average (1991–2020).

Table 3

Maize average emergence in days after planting and emergence uniformity (T_{10-90}), from ten year-fields by yield stability zone (YSZ). Variation coefficient in brackets.

Site	Year-Field	Emergence- days after planting†				Emergence uniformity (T_{10-90})†			
		HS	MS	LS	UN	HS	MS	LS	UN
Springport	2016–222	10.9b (11)[§]	11.5a (13)	11.4a (12)	10.7b (6)	1.6	2.3	2.4	1.0
	2017–222	5.5b (32)	5.2b (41)	6.4a (47)	4.9b (26)	2.7bc	3.5ab	5.4a	1.0c
	2018–105	7.0 (10)	7.2 (13)	—	7.1 (19)	3.0	3.0	—	3.0
	2019–304	8.1 (8)	8.0 (8)	—	8.2 (12)	1.4	1.5	—	1.3
	2020–308	14.4 (10)	14.7 (9)	14.7 (9)	14.7 (15)	4.0a	1.6b	2.1b	1.5b
	2021–210	10.8c (17)	11.2cb (22)	13.2a (26)	11.8b (9)	2.6b	4.2ab	6.8a	4.3ab
Portland	2017-JS1	10.3a (11)	10.4a (15)	10.5a (8)	9.8b (11)	2.0	1.3	1.4	2.0
	2018-NC12	11.6a (14)	10.1b (12)	—	10.7b (13)	3.0	3.0	—	4.0
	2019-MG1	8.9c (10)	11.4a (16)	9.8b (6)	9.4bc (6)	1.4b	3.4a	1.0b	1.0b
Parana	2020–11	7.5ab (31)	7.1ab (12)	6.9b (27)	—	3.0	2.0	2.0	—
ANOVA									
Year-Field			ns				ns		
YSZ			ns				ns		
Year-Field x YSZ			***				*		

† Means not sharing the same letter within the same row are different ($p < 0.05$) from each other. [§]Values in parentheses represent the coefficient of variation within each YSZ. HS: High and stable, MS: Medium stable, LS: Low stable, and UN: Unstable.

fields with a John Deere 1770 NT and a pneumatic Giorgi Precisa 8000 was used in Parana field.

2.2. Yield stability zones delineation

Yield stability zones (YSZ) in the Michigan fields were delineated from several years of yield monitor data collected from farmers in each studied field following (Basso et al., 2007; Maestrini and Basso, 2018). Briefly, standardized yield maps were used to calculate the mean (μ) and standard deviation (σ) of the yield for every pixel of the field, considering a pixel as stable when $\sigma < 0.75$ and as unstable when $\sigma \geq 0.75$. Similarly, pixels with $\mu < 0$ were classified as low-yielding and high-yielding when $\mu > 0$. This methodology classifies field pixels as High Stable (HS), Low Stable (LS), Medium Stable (MS) and Unstable (UN). As Parana fields lacked yield maps data, productivity zones were determined based on detailed soil maps, soil productivity index maps, and using farmer experience (Hornung et al., 2006). It was therefore not possible to estimate the temporal variation in the productivity and the unstable zones in this field.

2.3. Experimental design

Three replicate plots were established in each field and in each identified yield stability zone shortly after maize planting (0–2 days after planting, DAP), covering an area of two meters by four-rows in 2016 (Field 222), 2017 (Field 222 and Field JS1), and 2018 (Field 105 and Field NC12) and five meters by two-rows in 2019 (Field 304 and Field MG1), 2020 (Field 308 and Field 11), and 2021 (Field 210). In each case plot size allowed for up to 60 plants per plot (Fig. 1). Fields in Springport, except for 2019-F304, had cover crop coverage at planting, which were terminated one week after planting.

2.4. Plant emergence measurements

In 2016 and 2017, emergence dates were estimated from time-lapse images (one per hour) taken between dawn and dusk by ‘Stealth Cam’ cameras (16–22 MP resolution) that were attached to a post five rows in front of each replicate plot. The emergence dates were determined by analyzing the imagery using the ESRI ArcGIS Image Analysis toolbox, and the distance between the plants within each row was measured in the field.

From 2018–2021, emergence was recorded by visiting each plot in each field once per day during the period of emergence. Each emerged plant was individually identified using white stakes labeled with permanent ink that indicated the number of days after planting to emergence (Fig. 1), and the distance between the plants within the row was measured and recorded (Fig. 1). In order to evaluate plant spatial variation, plant growing space (GS, cm^2 $plant^{-1}$) was calculated as the sum of the half distances between a plant and its two neighbors multiplied by the row spacing (Eq. 1; (Martin et al., 2005)):

$$GS_i=[(d_i-d_{i-1})/2+(d_{i+1}-d_i)/2)xR] \quad (1)$$

where GS_i is the *i*th plant space available to grow, d_i, d_{i-1}, and d_{i+1}, are the distances to the *I*, *i*-1, and $i+1$ plant, and R is the row spacing. Additionally, each plant or space between plants was classified according to the distance within the row as a “double”, “skip” or “uniform” (Novak and Ransom, 2018). The classification was made based on the standard deviation of the distance between plants within the row and the theoretical distance between the plants i.e., expected distance between plants based on plant density and row spacing. According to plant density and row spacing in Table 1, the calculated theoretical distance was 18, 20 and 27 cm, for Springport, Portland, and Parana, respectively. Thus, doubles were identified as consecutive plants less than 5 cm from each other. Skips were plants next to gaps greater than the theoretical distance between plants plus one standard deviation, and

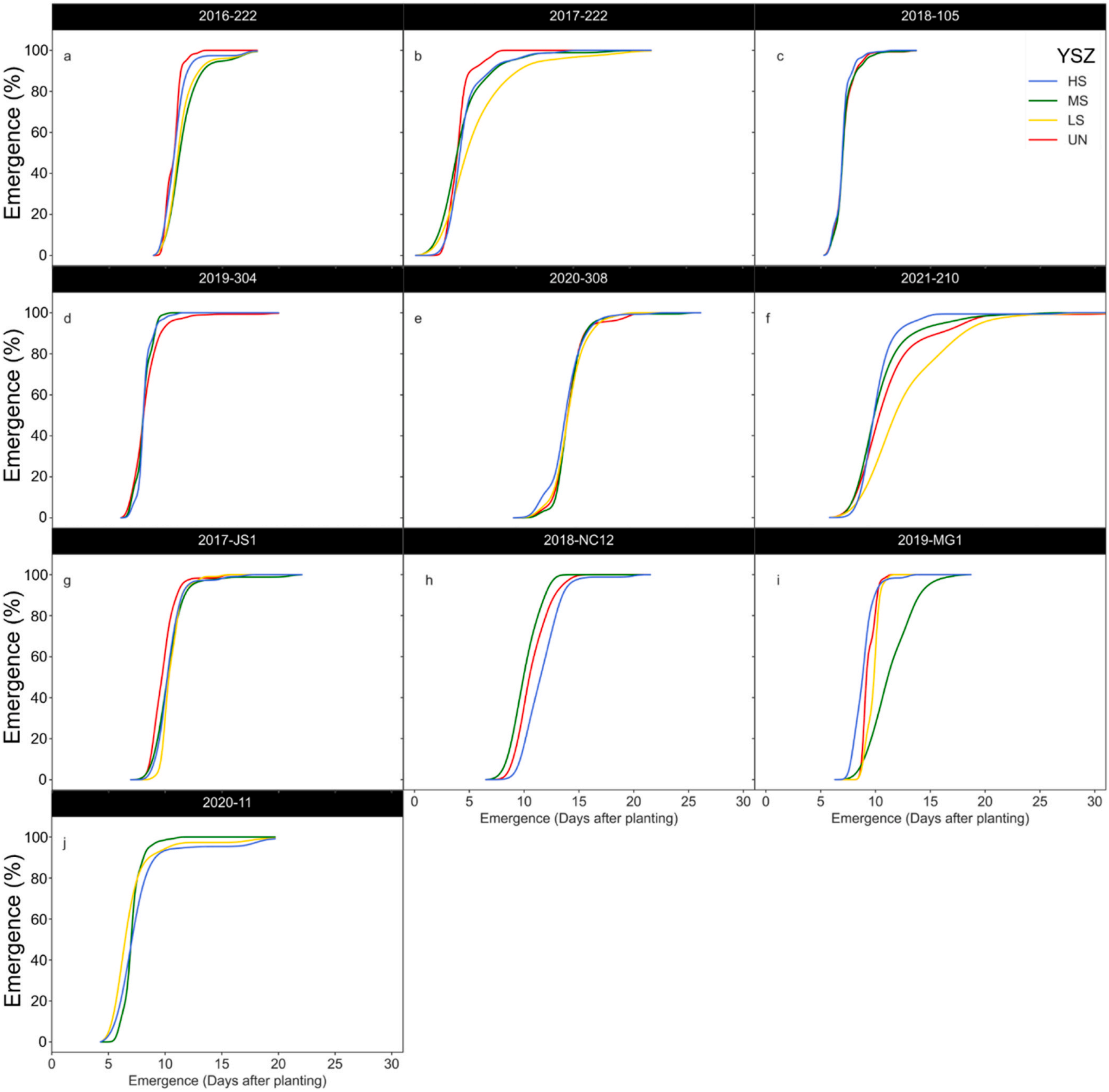

Fig. 2. Maize emergence cumulative distribution by Year-Field and Yield Stability Zone in the three evaluated sites Springport (a, b, c, d, e, and f), Portland (g, h, and i), and Parana (j). a) 2016–222, b) 2017–222, c) 2018–105, d) 2019–304, e) 2020–308, f) 2021–210, g) 2017-JS1, h) 2018-NC12, i) 2019-MG1, and j) 2020–11. HS: High and stable, LS: Low and stable, MS: Medium and Stable, and UN: Unstable.

uniform were plants with distances between 5 and the theoretical distance plus one standard deviation. At the end of the growing season, each labeled plant was individually harvested (n = 4186 plants) to analyze the individual plant yield (i.e. total grain weight per plant), grain number (grain per plant), and grain weight (i.e. individual grain weight). Crop yield per hectare was calculated by multiplying the plant yield (in grams per plant) with the plant density (in plants per square meter). Similar approach used in crop simulation models, where a single plant yield is upscaled to the crop level (Brown et al., 2014).

2.5. *Weather conditions*

A summary of long-term patterns of precipitation and temperature around planting and for the growing season are presented in Table 2. Rainfall during the growing season was closer (90–110 %) to the average (1991–2020) for the same period in most evaluated fields, whereas, in 2017 (Field 222 and JS1) in-season precipitation was between 28 % and 46 % lower than the average. Temperatures were slightly higher than historical averages in Springport fields, while they were within the range of historical values for the other four fields. The average temperature during the emergence period (May-June) ranged from 14° to 22°C in

Table 4
Mean growing space (cm^2 $plant^{-1}$) by yield stability zone (YSZ) at three locations (Springport, Portland, and Parana) across fields and years (2016–2021).

Location	Year-Field	YSZ *P*-value	Growing space (cm^2 $plant^{-1}$)†			
			HS	MS	LS	UN
Springport	2016–222	ns	—	—	1568	1528
	2017–222	<0.0001	1395b	1244b	1697a	1205b
	2018–105	ns	1313	1349	—	1368
	2019–304	ns	1217	1220	—	1269
	2020–308	0.0021	1524b	1570b	1649ab	1923a
	2021–210	<0.0001	1313b	1302b	1423a	1259b
Portland	2017-JS1	ns	1042	1001	998	1008
	2018-NC12	ns	1067	1068	—	—
	2019-MG1	ns	1632	1622	1564	1488
Parana	2020–11	ns	1578	1601	1617	—
ANOVA						
Year-Field				ns		
YSZ				ns		
Year-Field x YSZ				*		

—: Not measured, ns: non-significant, † Means not sharing the same letter within the same row and Year-Field are different ($p < 0.05$) from each other. ns: non-significant, $^*p < 0.05$

Springport, around 14 % higher than the 30 yr average for the same period. In contrast, temperatures in Portland were 16 % higher than average in May but 7 % lower in June. In Parana, temperatures during the emergence period (Dec-Jan) were slightly lower (2 %) than the 30-yr average. The average precipitation during the evaluated crop emergence period was slightly below the 30-yr average in May (4 %) and above it in June (12 %) in Springport, and in Portland, it was slightly below the 30-yr average in May (6 %) and June (3 %). Parana showed below-average precipitation in December (21 %) and above average in January (56 %) (Table 2).

2.6. Data analysis

Data was analyzed using the GLIMMIX procedure in SAS version 9.4 (SAS Inst., Inc.), to test the effects of Year-Field and YSZ and their interaction (Year-Field x YSZ) on plant emergence and growing space, YSZ and Year-Field x YSZ were considered fixed effects and Year-Field random. Individual plants were nested within each plot and included as a random factor to identify them as subsamples. Additionally, emergence was described using the 10, 50, and 90 percentiles of the emergence distribution, emergence uniformity was calculated as the time between the 10 % and 90 % of emergence (Egli and Rucker, 2012). Plant yield, grain number, grain weight, and crop yield were analyzed by field to test the effect of YSZ, considering DAP and GS as covariates. Mean separation between groups was analyzed using Tukey's method, performing pairwise comparisons to identify differences greater than the expected standard error. In addition, to make results comparable among Year-Fields the relative to the maximum per Year-Field plant yield (RPY), grain number (RGN), and crop yield (RY) were calculated and a regression analysis was performed using the JMP® Pro Version 15.2.0 (SAS Institute Inc., Cary, NC, 1989–2021) to determine relationships with DAP using the mean RPY, RGN, and RY per day of emergence per plot. Slopes and intercepts were compared by yield stability zones, when no differences among slopes were detected, multiple regressions were performed using YSZ as a dummy variable to select a model that best describes the relationship. Three models were compared: i) Full model, describe the relationship using four or three functions one per YSZ (8 or 6 parameters), ii) Simple model with YSZ, describes the relationship

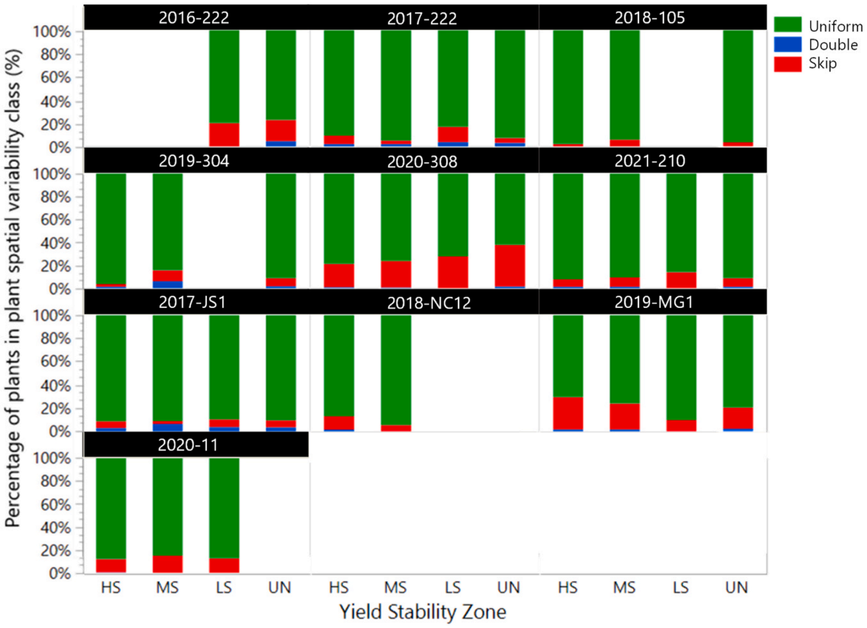

Fig. 3. Plant spatial variability within the maize's row as percentage of uniform, skip, and double plants by yield stability zone across fields and years. Uniform: plants with distances between 5 cm and the theoretical distance plus one standard deviation; Skip: gaps greater than the theoretical distance plus one standard deviation, and Double: consecutive plants less than 5 cm from each other. HS: High stable, MS: Medium stable, LS: Low stable, and UN: Unstable.

Table 5

Average plant yield (g $plant^{-1}$), grains number grains $plant^{-1}$), grain weight (g $grain^{-1}$), and crop yield (Mg ha^{-1}) by yield stability zone (YSZ) at three locations (Springport, Portland, and Parana) across fields and years (2016–2021).

Site	Year-Field	YSZ	Plant yield† g $plant^{-1}$	Grain number† grains $plant^{-1}$	Grain weight† g $grain^{-1}$	Yield† Mg ha^{-1}
Springport	2016–222	HS[§]	163	553	0.294	11.8a
		MS[‡]	162	536	0.304	10.5b
		LS[¶]	150	496	0.306	10.7b
		UN[‡]	160	506	0.318	11.6a
	2017–222	HS	130a	465	0.280b	12.4b
		MS	150a	499	0.300a	13.3a
		LS	109b	403	0.271c	7.7d
		UN	116a	415	0.278bc	10.6c
	2018–105	HS	141	480	0.293	10.8
		MS	133	470	0.285	10.1
		UN	146	496	0.296	10.8
	2019–304	HS	173	572	0.302	12.
		MS	142	511	0.275	10.62
		UN	150	510	0.291	10.8
	2020–308	HS	208b	638b	0.328a	12.7
		MS	202b	644b	0.313b	11.8
		LS	143c	657ab	0.215c	7.5
		UN	238a	713a	0.336a	11.7
	2021–210	HS	145a	557a	0.262	10.2a
		MS	131b	533ab	0.249	9.4b
		LS	126b	503b	0.251	8.4c
		UN	108c	437c	0.265	8.0c
Portland	2017-JS1	HS	131	414	0.315	9.3
		MS	118	393	0.301	8.9
		LS	86	278	0.312	6.4
		UN	117	370	0.318	8.6
	2018-NC12	HS	98	432	0.233	9.3
		MS	167	525	0.319	15.4
		UN	120	475	0.250	11.1
	2019-MG1	HS	137	462	0.293	11.39
		MS	113	377	0.304	9.5
		LS	99	329	0.309	8.48
		UN	119	375	0.324	10.9
Parana	2020–11	HS	101a	447a	0.230	6.6a
		MS	113a	442a	0.253	7.3a
		LS	71b	309b	0.236	4.5b
ANOVA						
Year-Field			ns	ns	ns	ns
YSZ			ns	ns	* *	* *
DAP			* **	* **	ns	ns
DAP x YSZ			ns	ns	*	*
Year-Field x YSZ			* **	* **	* **	* **
Year-Field x YSZ x DAP			* **	* **	* **	* **

†Means not sharing the same letter within the same column and field-year are different ($p < 0.05$) from each other. ns: non-significant, *$p < 0.05$,* *$p < 0.01$, * **$p < 0.001$, §HS: High and stable, ‡LS: Low and stable, ¶MS: Medium and Stable, ‡UN: Unstable.

using a unique function (5 or 4 parameters) using dummy variables, and iii) Simple model that describes the relationships with a unique function (2 parameters) (Supplemental Table S3). Models were compared with a F test (Mead et al., 2003) selecting the simplest model (less parameters) that better described the relationships.

3. Results

3.1. Emergence by year-field and yield stability zones

Across all fields, emergence ranged from 3 to 31 days after planting (DAP). The emergence range was highest in Springport (3–31 DAP), and narrower in Portland (5–25 DAP) and Parana (6–25 DAP). There was a significant interaction Year-Field x YSZ on emergence and emergence uniformity (Table 3). All yield stability zones (YSZ) showed variability in emergence and emergence was significantly affected by YSZ in seven out of ten field site years ($p < 0.05$) (Table 3). In the fields were emergence was significantly affected by YSZ, it was more delayed in the LS, except in 2019-MG1 where MS was more delayed compared with the other zones, and in 2020–11 where the HS and MS showed a more delayed emergence.

The time to 10 %, 50 %, and 90 % of emergence were not significantly affected by Year-Field and YSZ, and their interaction (Supplemental Table S1). The emergence uniformity ($T_{10–90}$) showed a significant Year-Field x YSZ interaction, and four out of ten fields showed significant YSZ effect in $T_{10–90}$. In 2017–222 and 2021–210 year-field from Springport, the time between 10 % and 90 % emergence was higher in the LS zone (Fig. 2b and f, Table 3), whereas in 2020–308 the HS had higher time between 10 % and 90 % of emergence (Fig. 2e). In 2019-MG1 emergence showed less uniformity (i.e. higher time between 10 % and 90 % of emergence) in the MS zone (Fig. 2j).

3.2. Plant spatial variability by yield stability zones

The available space that plants had for growth (GS) calculated to evaluate the plant spatial variability, ranged from 998 to 1632 cm^2 per plant. In Springport, three fields showed significant differences in GS ($p < 0.05$) between YSZ (Table 4), ranging from 1217 to 1524, 1423–1697, 1220–1570, and 1205–1923 cm^2, in the HS, LS, MS, and UN YSZs, respectively. The GS in Portland fields ranged from 1042 to 1632, 998–1564, 1001–1622, and 1008–1488 cm^2, in the HS, LS, MS, and UN YSZs, respectively. In Parana, GS was 1578, 1617, and 1601 cm^2, in the HS, LS and MS YSZs, respectively.

Based on within row plant spacing, plant spatial variability was also

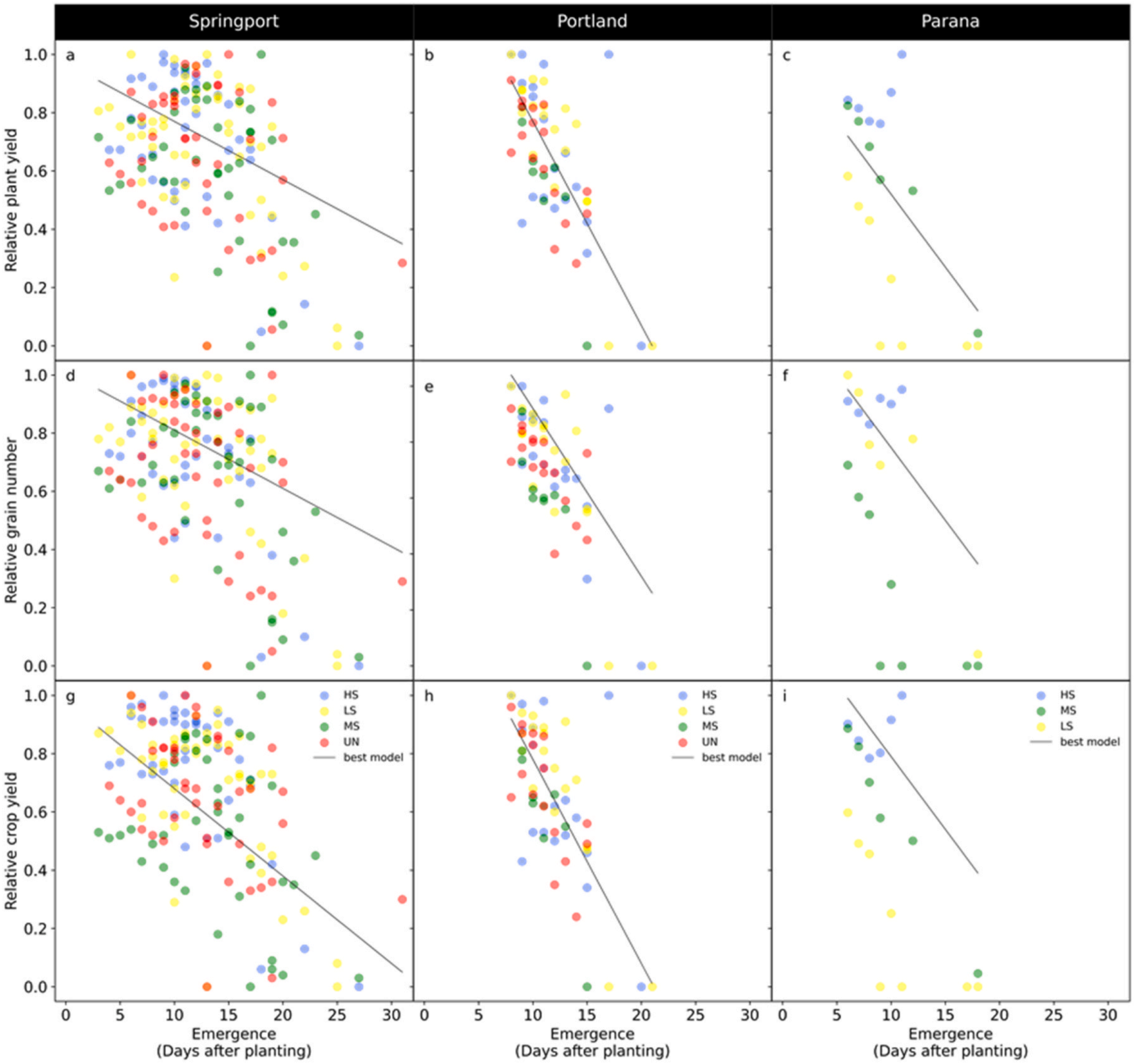

Fig. 4. Relative plant individual yield (a, b, c), relative grain number (d, e, f) and relative crop yield (g, h, i) as affected by emergence (days after planting) and yield stability zone for three sites Springport, Portland, and Parana. HS: High and stable, LS: Low and stable, MS: Medium and Stable, and UN: Unstable. Each point represents the mean value per emergence day in each plot.

evaluated by classifying individual plants as uniform, skip or double. In Springport, plots contained between 76 % and 96 % uniform plants, between 4 % and 23 % skips, and between 0 % and 3 % doubles. In Portland uniform plants were between 81 % and 91 %, skips represented 4–17 %, while doubles were between 1 % and 4 %. Similarly, the Parana field had 87 % uniform plants, 12 % skips, and 1 % doubles (Fig. 3).

3.3. Plant yield, crop yield and yield components

Individual plant yield, grain number per plant, individual grain weight and crop yield, were significantly affected by the interaction Year-Field x YSZ x DAP ($p < 0.001$, Table 5). Individual plant yield ranged from 71 to 238 g plant^{-1}, and when affected by YSZ it was consistently lower in the LS zone (Table 5). The instability of UN zone was evident, in 2020–308 plant yield in this zone was 238 g plant^{-1}, whereas in 2021–210 it reached 108 g plant^{-1}.

Grain number per plant ranged from 309 to 713 grain plant^{-1}, it was affected by YSZ in three year-fields with variable results (Table 5). In 2020–308 and 2020–11 LS zone had higher grain number than the other zones, whereas in 2021–210 Un zone had the lowest grain number per plant. Individual grain weight ranged from 0.215 to 0.324 g grain^{-1}, it was generally lower in the LS zone.

Crop yield ranged from 4.5 to 15.39 Mg ha^{-1}, it was significantly affected by the YSZ in four year-fields, been consistently lower in the LS zone (Table 5). The lack of significant differences in some year-fields might be related to the high plant-to-plant variability.

3.4. Impact of emergence delay on plant yield, crop yield and yield components

The relative individual plant yield across year-fields was negatively affected by emergence delay (Fig. 4a, b, c). The average relative plant yield decrease per day of emergence delay was 2 % in Springport and it did not show differences among YSZ (Table 6 and Supplemental Table S2). Although, there were no significant differences between YSZs (i.e., no significant difference in slopes, $p > 0.05$) in the emergence effect, Portland and Parana relative plant yield was best explained with a model that included the zones as dummy variables (Table 6 and Supplemental Table S2). Similarly, relative grain number was significantly reduced by the delay in emergence (Fig. 4d, e, and f). In Springport the relationship was best explained with a simple model and the reduction in RGN was 2 % per day of delay in emergence. In Portland and Parana, the model that included YSZs as dummy variables explained the best the reduction in RGN (Table 6 and Supplemental Table S2). In Springport,

Table 6
Models that best describe the relationship between relative plant yield (RPY), relative grain number (RGN), and relative crop yield (RY) with plant emergence in three sites.

Site	Variable	Model	R^2	p
Springport	Relative Plant yield	RPY = 0.97 − 0.02DAP	0.24	* **
	Relative grain number	RGN = 1.01 − 0.02DAP	0.25	* **
	Relative crop yield	RY = 0.98 − 0.03DAP	0.27	* **
Portland	Relative Plant yield	RPY = 1.47 + 0.04MS − 0.15LS − 0.08UN − 0.07DAP	0.58	* **
	Relative grain number	RGN = 1.52 − 0.02MS − 0.21LS − 0.09UN − 0.06DAP	0.63	* **
	Relative crop yield	RY = 1.48 + 0.05MS − 0.14LS − 0.06UN − 0.07DAP	0.57	* **
Parana	Relative Plant yield	RPY = 1.02 − 0.32MS - 0.20LS − 0.04DAP	0.84	* **
	Relative grain number	RGN = 1.25 − 0.40MS - 0.11LS − 0.05DAP	0.83	* **
	Relative crop yield	RY = 1.29 − 0.21MS − 0.54LS − 0.05DAP	0.85	* **

***$p < 0.0001$; HS: High and stable, LS: Low and stable, MS: Medium and Stable, and UN: Unstable

the relative crop yield relationship with emergence was best explained by a simple model, and the reduction was 3 % per day of delay. In Portland and Parana, a model including YZS as dummy variables best explained the relationship with emergence, the reduction in RY were 7 % and 5 % per day of delay in the emergence in Portland, and Parana, respectively (Table 6 and Supplemental Table S2). The effect of emergence delay on individual grain weight (Supplemental Table S2) was not significant ($P > 0.05$).

3.5. Impact of plant available growing space variation on plant yield, crop yield and yield components

Although some fields showed a notable effect of growing space on individual plant yield, grain number, grain weight, and crop yield (Supplemental Table S2), none of the regressions were significant (Supplemental Fig. S4). Plant yield was significantly ($p < 0.05$) affected by within row plant separation (uniform, skip or double) in field 2017-FJS1 in favor of plants classified as skips (Table 7), and in 2018-FNC12 in favor of plants classified as uniform. The grain number was significantly affected by the within row plant separation in two fields (2017-FJS1 and 2020-F308) where the plants located in skips produced more grains. The individual grain weight was affected by the distance between plants in field 2017-F222, where plants classified as skips reached higher individual grain weight. Similarly, crop yield showed a significant variation with the variation in the distance between plants in the three fields (2016-F222, 2017- FJS1, and 2018-FNC12), and yield was higher in the uniform plants except in 2017-FJS1 where yield was higher for plants classified as skips (Table 7).

3.6. Spatial and temporal variability impact on plant yield, grain number and yield variability

Spatial and temporal variability was assessed as the distance between plants coefficient of variation and emergence coefficient of variation. Spatial variability did not cause a significant effect in the variability of relative plant yield, relative grain number, and relative yield (Fig. 5a, c, and e). In contrast, temporal variability caused a significant impact in the three variables. Moreover, there was an increase in the variability of relative plant yield, relative grain number, and relative yield with the increase in emergence variability (Fig. 5b, d, and f).

4. Discussion

The impacts of emergence time and spatial variability of within row planting are rarely studied outside the confines of small experimental research plots. In this study we worked exclusively on active, commercial farmer fields that experienced a range of management practices (e.g., seeding rate, soil type and conditions, cover crop, tillage, and crop hybrid) with single planting dates at each site to evaluate the spatial and temporal variation of maize emergence in the various sub-field yield stability zones. Our results showed that emergence delay has a greater impact than plant spatial variation on crop yield and its components, and in general the impact is larger in low yield stability zones (i.e. higher coefficient for the LS zone in the model, Table 5). The greater impact in the low yield stability zones might be related to spatial variation in the conditions that promote delayed emergence (Knappenberger and Köller, 2012) i.e., less plant available water and reduced soil fertility in the low yielding areas. It is noteworthy that the LS zones in Michigan sites were typically located in the header of the fields, where field operation transit is higher, likely leading to compaction and decreasing soil water retention. In Parana, the LS zone was in a severely eroded area that retains less water and has lower fertility.

In our study, emergence across years and fields varied between 3 and 31 DAP, a broader range than reported by Nemergut et al. (2021), who evaluated in-field maize emergence in different soils and at different planting depths and reported emergence between 4 and 13 DAP. This

Table 7
Average plant yield (g plant^{-1}), grain number (grains plant^{-1}), grain weight (g grain^{-1}), crop yield (kg ha^{-1}), by plant spatial variability class (Uniform, Skip, and Double) at three locations (Springport, Portland, and Parana) across fields and years (2016–2021).

Location	Year-field	Plant yield† (g plant^{-1})			Grain number† (grain plant^{-1})			Grain weight† (g grain^{-1})			Yield† (kg ha^{-1})		
		Uniform	Skip	Double	Uniform	Skip	Double	Uniform	Skip	Double	Uniform	Skip	Double
Springport	2016–222	155	148	156	501	484	507	0.313	0.307	0.312	11334a	9747b	11289ab
	2017–222	127	131	109	447	441	405	0.282ab	0.292a	0.265b	11085	9894	9697
	2018–105	141b	181a	—	494	552	——	0.290	0.328	——	11614	13155	——
	2019–304	154	182	146	529	602	522	0.289	0.301	0.277	11408	13328	10896
	2020–308	189	230	158	643b	734a	593b	0.294	0.314	0.265	10924	11915	9374
	2021–210	126	142	145	503	546	546	0.256	0.266	0.264	8888	9831	10134
Portland	2017-JS1	112b	137a	121ab	361b	430a	376ab	0.311	0.320	0.327	8230b	9737a	8949ab
	2018-NC12	134a	103b	104ab	483	383	350	0.277	0.252	0.277	12491a	9307b	9837ab
	2019-MG1	117	134	94	385	418	327	0.307	0.320	0.290	10004	11424	8230
Parana	2020–11	96	93	73	403	391	320	0.240	0.239	0.225	6224	5942	4848

†Means not sharing the same letter within the same row are different ($p < 0.05$) from each other. Uniform: plants with distances between 5 cm and theoretical distance plus one standard deviation; Skip: plants located gaps greater than theoretical distance plus one standard deviation, and Double: consecutive plants less than 5 cm from each other.

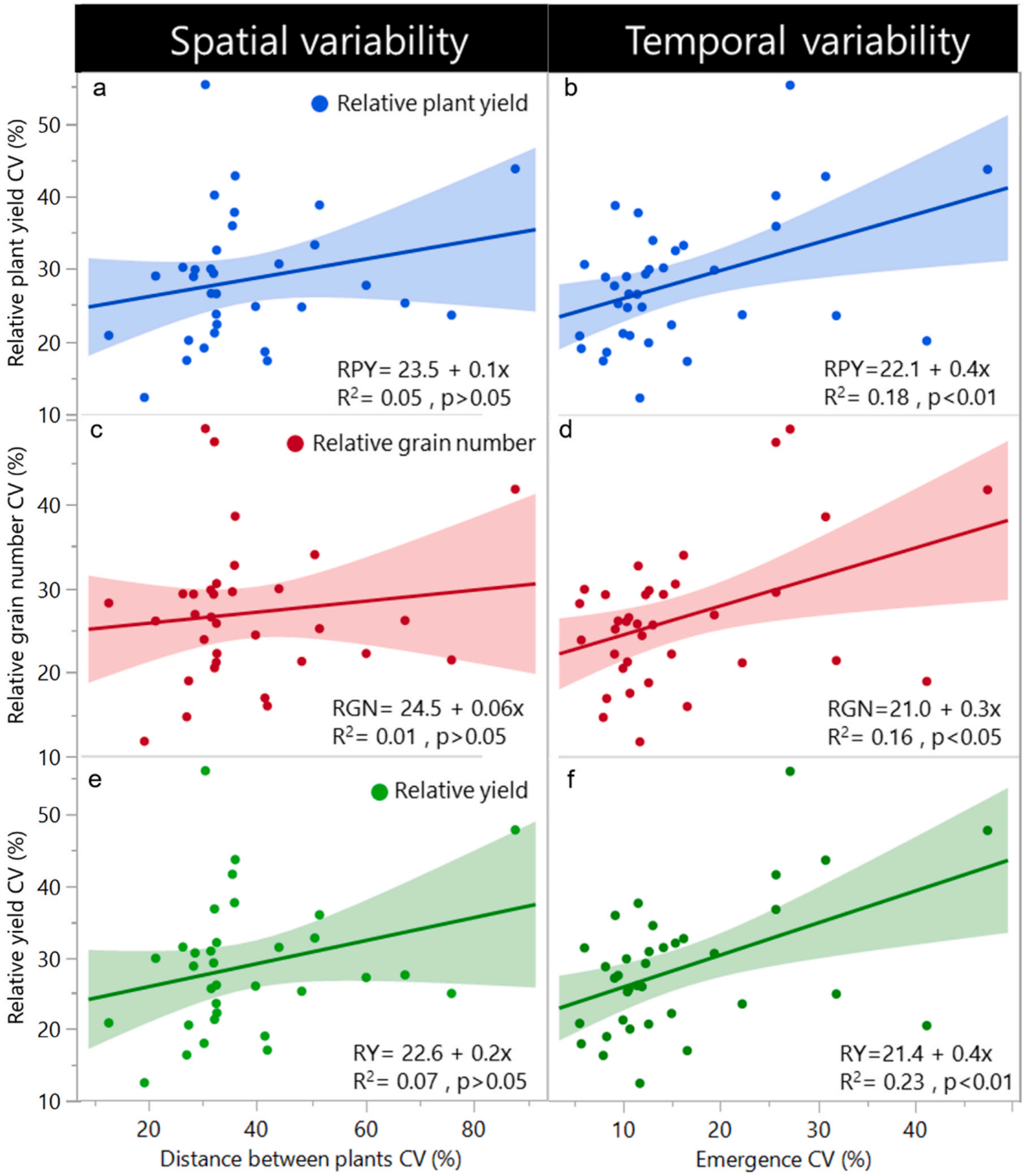

Fig. 5. Spatial and temporal variability effect on relative plant yield variability (a and b), relative grain number variability (c and d), and relative yield variability e and f).

narrower emergence range may be related to their observation period – results were reported over 14 consecutive DAP, so later emerging plants were not included in the analysis. Overall, emergence time variation was higher in Springport than in Portland and Parana (Fig. 3a). The difference in emergence between the Michigan sites might be explained by different tillage practices adopted; Springport fields were under no-till with cover crops in some years, which may have resulted in colder and wetter soils than in Portland where conventional tillage was used. Differences in surface residue cover related to tillage systems have been shown to affect soil temperature and consequently maize emergence (Gupta, 1985). Even though the Parana field was under no-till, there was a higher uniformity in emergence time when compared with Springport and Portland. This could be related to the higher mean temperature at the Parana site along with the later planting date that can lead to higher soil and near soil surface air temperatures, major factors known to affect emergence (Knappenberger and Köller, 2012). Planting speed is an important contributing factor to plant emergence time and one that farmers can directly control. Planting speed is related to the depth that the seed is placed; greater speeds increase the variability in the seed depth placement, which in turn increases the variation in timing of plant emergence (Nielsen, 1993). Seeds planted in a shallower position with enough water and appropriate temperature for emergence will do so faster than seeds planted deeper. However, seeds that are planted at shallower depths and that do not have good soil-seed contact, or where the soil is dry (Cox and Cherney, 2015), will not emerge, leading to a greater stand variability with more exposure to bird and other animal predation. Consequently, the optimum planting speed should one that allows the planter to set the seed at the desired planting depth.

Our results showed a significant negative effect of the increasing delay of emergence on relative individual plant yield, relative grain number and relative crop yield ($p < 0.05$, Fig. 5). Although the degree of decrease per day of delay in the emergence (slopes) of the relationships for the variables (relative plant yield, relative grain number, and relative yield) and emergence did not significantly differ among YSZ, the maximum attainable yield by YSZ, in Portland and Parana the models that best explained the relationship between the variables and emergence, included the YSZ as dummy variables (Table 6) generally penalizing LS zones. Consequently, by considering variable rate seeding based on YSZs, farmers could reduce their seeding rate in the LS zones, thereby reducing seed cost, a major portion of total planting costs. For each day of delay in emergence, relative individual plant yield was reduced on average by 4 %, a similar magnitude to those found by (Andrade and Abbate, 2005), (Liu et al., 2004b), and (Nafziger et al., 1991). Emergence delay appears to promote the formation of plant hierarchies (Rossini et al., 2018), where plants that emerge earlier have an advantage in that they have access to more readily available resources and can uptake their requirement, when compared to plants that emerge later that may not (Carter et al., 1990).

A significant reduction was found in the number of grains per plant (Fig. 5d, e, and f, Table 6), whereas the effect on grain weight per plant was less consistent (Supplemental Table S2). This result is similar to Pommel et al. (2002), who evaluated heterogeneity in three emergence treatments (normal, late, and delayed) and found a more frequent negative effect of treatment on grain number than on individual grain weight as emergence time increased. Maize with uneven emergence will likely develop plant hierarchies, where plants that emerge late will experience a higher competition for resources from early emerged and better stablished plants (Pagano and Maddonni, 2007). Additionally, as the late emerged plants will have a phenological delay, postharvest damage and costs might increase due to grains from late emerging plants that will have higher grain moisture content at harvest.

Although the individual grain weight was generally not significantly affected by the emergence delay (Supplemental Table S2), the reduction in the grain number was sufficient alone to significantly reduce the final crop yield, with reductions ranging from 416 to 903 kg ha^{-1} per day of delay (3–14 % decrease), higher than the 293 kg ha^{-1} reduction in yield per day of delay reported by Liu et al. (2004a) and the 122 kg ha^{-1} per day found by Rutto et al. (2014). Differences probably related to the methodology; these authors used manipulative treatments to achieve the delayed emergence (i.e., planting at different dates) in contrast with our experiments where the natural variation of emergence was captured. The temporal variability in emergence affects resource capture and utilization by the plants, causing a decrease in grain yield through a reduction in harvest index (Tollenaar et al., 2006).

The plant available growing space varied between site location (Table 4), an expected outcome due to the differences in plant density and row spacing between the fields (Table 1). We found that the plant spatial variability differs with YSZ in three of the ten fields, and in general plants in the low stable YSZ had a larger available space than in the other YSZs. This can be related to a higher percentage of skips in the low stable yielding zones, that probably caused a reduction on plant population as well on yield. Although the GS had a significant effect in some fields, there was no significant relationship between growing space and yield and yield components (Supplemental Table S2). Tollenaar et al. (2006) demonstrated that plants located next to a gap (i.e., a 'missing' plant) increased their yield, but that this is insufficient to compensate for the gap. However, Liu et al. (2004b) reported that standard deviations lower than 16 cm does not cause plant competition, a range that includes the standard deviation in our experiments (6–10 cm).

The availability of precision planting equipment has allowed producers to reduce the variability within the row and obtain a more consistent distance between the plants, as observed by the small percentage of skips and doubles found in our fields (Fig. 3), where for example, the pneumatic planter used in Parana – specially developed for the no-tillage system probably contributed to a more uniform stand. Shuai et al. (2019) analyzed maize stand heterogeneity using unmanned aerial vehicles (UAVs) across YSZs and concluded that variability in plant spacing across YSZs was not a major cause of yield variability. This result agrees with other studies that found that plants can partially compensate for grain yield penalties due to greater plant spatial variability if the plant density is adequate (Lauer and Rankin, 2004), which is likely the case in our experiments where fields were managed by their owners who have optimized the inputs.

Variation in plant emergence time has a stronger effect than variation of within-row plant spacing (Fig. 5 and Supplemental Table S2), agreeing with previous studies (Lauer and Rankin, 2004; Liu et al., 2004a; Pommel et al., 2002), and likely related to lower overall spatial variability when compared to temporal variability. In addition, the plants may have compensated for within row variations (i.e., missing plants or doubles), but were unable to do so for temporal variations where plant hierarchies developed due to resource availability and capture. The data and mechanisms that explain the effects of spatial and temporal variation of delayed emergence on crop yield should be incorporated into simulations models to improve their accuracy in crop yield forecasting at small and large scales.

5. Conclusions

Temporal variability of crop emergence had a larger impact than within-row plant spatial variability on final crop yield and its components. The delay in emergence caused a decrease in maize total yield and yield components that was not statistically related to yield stability zone type but was more prevalent in low yield stability zones. The reduction in total crop yield could be explained by the reduction in the grain number per plant.

Our findings can be incorporated into crop models that currently do not consider naturally occurring emergence variation, but rather assume uniform emergence that might lead to yield overestimation. Future work is needed to incorporate the relationship of emergence delay with plant individual yield, grain number and grain yield into crop models to improve model accuracy.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data Availability

Data will be made available on request.

Acknowledgements

The authors wish to thank Rich Price, Ruben Ulbrich, Lydia Price, and Neville Millar for their valuable support in field activities, data processing and comments on the manuscript. The authors are grateful to the funding provided by the US Department of Agriculture National Institute of Food and Agriculture: 2020-67021-32799, 2015-68007-23133, and Natural Resource Conservation Service award numbers NR213A750013G001 and MSU AgBioResearch.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2023.109090.

References

Andrade, F.H., Abbate, P.E., 2005. Response of maize and soybean to variability in stand uniformity. Agron. J. 97 (4), 1263–1269. https://doi.org/10.2134/agronj2005.0006.

Brown, H.E., Huth, N.I., Holzworth, D.P., Teixeira, E.I., Zyskowski, R.F., Hargreaves, J.N. G., Moot, D.J., 2014. Plant Modelling Framework: Software for building and running crop models on the APSIM platform. Environ. Model. Softw. 62, 385–398. https://doi.org/10.1016/j.envsoft.2014.09.005.

Carter, P., Nafziger, E., Lauer, J., 1990. Uneven emergence in corn. Corn. Agron. Wisc. Edu 344.

Cox, W.J., Cherney, J.H., 2015. Field-scale studies show site-specific corn population and yield responses to seeding depths. Agron. J. 107 (6), 2475–2481. https://doi.org/10.2134/agronj15.0308.

Daynard, T.B., Muldoon, J.F., 1983. Plant-to-plant variability of maize plants grown at different densities. Can. J. Plant Sci. 63, 45–59. https://doi.org/10.1163/1937240X-00002218.

Egli, D.B., Rucker, M., 2012. Seed vigor and the uniformity of emergence of corn seedlings. Crop Sci. 52 (6), 2774–2782. https://doi.org/10.2135/cropsci2012.01.0064.

Ford, J.H., Hicks, D.R., 1992. Corn growth and yield in uneven emerging stands. J. Prod. Agric. 5 (1), 185–188. https://doi.org/10.2134/jpa1992.0185.

Gupta, S.C., 1985. Predicting corn planting dates for moldboard and no-till tillage systems in the corn belt 1. Agron. J. 77 (3), 446–455. https://doi.org/10.2134/agronj1985.00021962007700030021x.

Hornung, A., Khosla, R., Reich, R., Inman, D., Westfall, D.G., 2006. Comparison of site-specific management zones: soil-color-based and yield-based. Agron. J. 98 (2), 407–415. https://doi.org/10.2134/agronj2005.0240.

Knappenberger, T., Köller, K., 2012. Spatial assessment of the correlation of seeding depth with emergence and yield of corn. Precis. Agric. 13 (2), 163–180. https://doi.org/10.1007/s11119-011-9235-4.

Kolling, D.F., Sangoi, L., Leolato, L.S., Panison, F., Coelho, A.E., Kuneski, H.F., 2019. Can an increase in nitrogen rate mitigate damages caused by uneven spatial distribution of maize plants at the sowing row? Acta Sci. - Agron. 41 (1), 1–9. https://doi.org/10.4025/actasciagron.v41i1.39874.

Lauer, J.G., Rankin, M., 2004. Corn response to within row plant spacing variation. Agron. J. 96 (5), 1464–1468. https://doi.org/10.2134/agronj2004.1464.

Lawles, K., Raun, W., Desta, K., Freeman, K., 2012. Effect of delayed emergence on corn grain yields. J. Plant Nutr. 35 (3), 480–496. https://doi.org/10.1080/01904167.2012.639926.

Liu, W., Tollenaar, M., Stewart, G., Deen, W., 2004a. Impact of planter type, planting speed, and tillage on stand uniformity and yield of corn. Agron. J. 96 (6), 1668–1672. https://doi.org/10.2134/agronj2004.1668.

Liu, W., Tollenaar, M., Stewart, G., Deen, W., 2004b. Response of corn grain yield to spatial and temporal variability in emergence. Crop Sci. 44 (3), 847–854. https://doi.org/10.2135/cropsci2004.8470.

Liu, W., Tollenaar, M., Stewart, G., Deen, W., 2004c. Within-row plant spacing variability does not affect corn yield. Agron. J. 96 (1), 275–280. https://doi.org/10.2134/agronj2004.2750.

Maestrini, B., Basso, B., 2018. Predicting spatial patterns of within-field crop yield variability. Field Crops Res. 219 (January), 106–112. https://doi.org/10.1016/j.fcr.2018.01.028.

Martin, K.L., Hodgen, P.J., Freeman, K.W., Melchiori, R., Arnall, D.B., Teal, R.K., Mullen, R.W., Desta, K., Phillips, S.B., Solie, J.B., Stone, M.L., Caviglia, O., Solari, F., Bianchini, A., Francis, D.D., Schepers, J.S., Hatfield, J.L., Raun, W.R., 2005. Plant-to-plant variability in corn production. Agron. J. 97 (6), 1603–1611. https://doi.org/10.2134/agronj2005.0129.

Mead, R., Curnow, R.N., Hasted, A.M., 2003. In: Chatfield, C., Lindsey, J., Tanner, M., Zidek, J. (Eds.), Statistical Methods in Agriculture and Experimental Biology, Third edition. Chapman & Hall/CRC.

Nafziger, E.D., Carter, P.R., Graham, E.E., 1991. Response of corn to uneven emergence. Crop Sci. 31 (3), 811–815. https://doi.org/10.2135/cropsci1991.0011183×003100030053x.

Nemergut, K.T., Thomison, P.R., Carter, P.R., Lindsey, A.J., 2021. Planting depth affects corn emergence, growth and development, and yield. Agron. J. 113 (4), 3351–3360. https://doi.org/10.1002/agj2.20701.

Nielsen, R.L. (1993). *Planting Speed Effects on Stand Establishment and Grain Yield of Corn*.

Novak, L., Ransom, J., 2018. Factors impacting corn (Zea mays L.) establishment and the role of uniform establishment on yield. Agric. Sci. 09 (10), 1317–1336. https://doi.org/10.4236/as.2018.910092.

Pagano, E., Maddonni, G.A., 2007. Intra-specific competition in maize: early established hierarchies differ in plant growth and biomass partitioning to the ear around silking. Field Crops Res. 101 (3), 306–320. https://doi.org/10.1016/j.fcr.2006.12.007.

Pommel, B., Mouraux, D., Cappellen, O., Ledent, J.F., 2002. Influence of delayed emergence and canopy skips on the growth and development of maize plants: A plant scale approach with CERES-Maize. Eur. J. Agron. 16 (4), 263–277. https://doi.org/10.1016/S1161-0301(01)00130-7.

Rossini, M.A., Otegui, M.E., Martínez, E.L., Maddonni, G.A., 2018. Contribution of the early-established plant hierarchies to maize crop responses to N fertilization. Field Crops Res. 216, 141–149. https://doi.org/10.1016/j.fcr.2017.11.015.

Rutto, E., Daft, C., Kelly, J., Chim, B.K., Mullock, J., Torres, G., Raun, W., 2014. Effect of delayed emergence on corn (Zea Mays L.) grain yield. J. Plant Nutr. 37 (2), 198–208. https://doi.org/10.1080/01904167.2013.859691.

Sangoi, L., Schmitt, A., Vieira, J., Junior, G.J.P., Souza, C.A., Casa, R.T., Schenatto, D.E., Giordani, W., Boniatti, C.M., Machado, G.C., 2012. Plant spacial variability in the sowing row and maize grain yield. Rev. Bras. De. Milho e Sorgo 11 (3), 268–277.

Shuai, G., Martinez-Feria, R.A., Zhang, J., Li, S., Price, R., Basso, B., 2019. Capturing maize stand heterogeneity across. Sensors (Switzerland) 19 (20). https://doi.org/10.3390/s19204446.

Tollenaar, M., Wu, J., 1999. Yield improvement in temperate maize is attributable to greater stress tolerance. Crop Sci. 39 (6), 1597–1604. https://doi.org/10.2135/cropsci1999.3961597x.

Tollenaar, M., Deen, W., Echarte, L., Liu, W., 2006. Effect of crowding stress on dry matter accumulation and harvest index in maize. Agron. J. 98 (4), 930–937. https://doi.org/10.2134/agronj2005.0336.