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Corn (*Zea mays L.*) seeding rate optimization in Iowa, USA

Mark A. Licht¹ · Andrew W. Lenssen¹ · Roger W. Elmore²

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Abstract Collecting soil, topography, and yield information has become more feasible and reliable with advancements in precision technologies. Combined with the accessibility of precision technologies and services to farmers, there has been increased interest and ability to make site-specific crop management decisions. The objective of this research was to develop procedures to optimize corn seeding rates and maximize yield using soil and topographic parameters. Experimental treatments included five seeding rates (61 750; 74 100; 86 450; 98 800; and 111 150 seeds ha⁻¹) in a randomized complete block design in three central Iowa fields from 2012 to 2014 (nine site-years). Soil samples were analyzed for available phosphorus (Olsen method), exchangeable potassium (ammonium-acetate method), pH, soil organic matter (SOM), cation exchange capacity (CEC), and texture. Topographic data (in-field elevation, slope, aspect, and curvature) were determined from publicly available light detection and ranging data. In four site-years, no interaction occurred between seeding rate and the descriptive variables. Three of the site-years resulted in a negative linear seeding rate response which made it impossible to determine an optimum seeding rate above the lowest seeding rate treatment. The seeding rate optimization process in five site-years resulted in seeding rate by variable interactions; four site-years had a single seeding rate by variable interaction (pH, in-field elevation, or curvature) and one site-year had three seeding rate by variable interactions (pH, CEC, and SOM). Meaningful seeding rate optimizations occurred in only three of nine site-years. There was not a consistent descriptive variable interaction with seeding rate as a result of weather variability.

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Introduction

Corn grain yields have increased since the 1930s in Iowa and across the U.S. Corn Belt. As corn grain yield increased, plant densities have also increased with a correlation of 0.65 (USDA-NASS 2015). Corn plant densities have increased by roughly 825 plants ha⁻¹ - year⁻¹ in Iowa since 2000 (USDA-NASS 2015). Currently, seeding rate recommendations that maximize yields for rainfed corn production in the central U.S. Corn Belt range from 69 000 to 98 800 seeds ha⁻¹ or more (Hoeft et al. 2000; Mueller and Sisson 2013; Nafziger 2012; Nielsen et al. 2015; Woli et al. 2014).

Corn yield exhibits a curvilinear response to increasing plant density where an optimal density can be determined. Up to the optimal plant density, the increase in total grain yield outweighs the reduction in yield per plant (Duncan 1984). After maximum yield is attained, competition for water, nutrients, and light become too great causing both field and per plant yields to decrease. Plant density yield response curves are influenced by biotic and abiotic factors (Shanahan et al. 2004; Van Roekel and Coulter 2011). Agronomists often assume that biotic yield-limiting factors such as incidence and severity of insects, weeds, and pathogens occur in-season and that these factors are minimized by management practices to as great an extent as possible in order to maximize yield. Abiotic factors that cause yield variability include topography as well as soil physical and chemical properties (Kaspar et al. 2004; Kravchenko and Bullock 2000; Kravchenko et al. 2003; Papiernik et al. 2005; Shanahan et al. 2004). The use of precision agriculture technologies offers the capability to better manage crop inputs and adjust for field variability associated with these abiotic factors.

Precision agriculture is based on the premise of using field information and advances in technology to manage crop requirements and agronomic practices in a site-specific manner to account for spatial and temporal variability (Bouma 1999; Hoeft et al. 2000; Mulla and Schepers 1997; Rawlins 1996; Searcy 1995). Early advances in precision agriculture included grid soil sampling, variable fertilizer applications, global positioning systems and yield mapping (Daberkow and McBride 1999; Mackay 1997; Taylor and Whelan 2010). Over the last two decades, variable rate seeding has developed from a concept to reality (Bullock et al. 1998; Clark and McGuckin 1996; Nafziger 2012). The advent of planter and monitor technology with the capability of planting at variable seeding rates across a field has given farmers and agronomists the ability to manage plant density using site-specific approaches to potentially increase productivity and profitability. Agronomists are now offering advice and services on variable rate seeding approaches.

Early in the adoption of variable rate seeding technology, Bullock et al. (1998) stated that for variable seeding to be profitable and productive, there needed to be a spatial relationship between yield and plant density as well as the influence of topographic and soil parameters on the relationship between grain yield and plant density. Therefore, these authors concluded that variable rate seeding would not be economically feasible at that time because of the difficulty in characterizing fields.

Initially site-specific, variable rate seeding determinations for corn were based on past yield productivity where higher yielding areas received higher seeding rates (Bullock et al. 1998; Butzen et al. 2012; Lowenberg-DeBoer 1999). However in Minnesota, Lamb et al.

(1997) found that neither higher nor lower yielding field areas were consistent from year to year and that only 4–42 % of grain yield variability in a given year was accounted for by grain yield from previous years.

As variable rate seeding technology becomes more widely available and other precision technology improves, variable rate seeding is now often based not only on past yield productivity but also soil fertility, soil texture, SOM, landscape position, in-field elevation or some combination thereof (Butzen et al. 2012; Doerge 1999; Gunzenhauser and Shanahan 2011). Many of these factors relate to corn yield variability. Previously in Iowa, Kaspar et al. (2003) determined that higher landscape positions and steep slopes had lower yield potential than lower landscape positions in years with below average rainfall. Conversely, depressions and slight hillslopes had lower yield potential than landscape positions conducive to topographic drainage in years with above normal rainfall. These findings confirmed earlier work by Spitze et al. (1973) showing grain yields in northeast Nebraska were influenced by soil drainage and topography, with lowland poorly drained areas having higher yield potential than slopes and ridgetops.

The goals of this research were to (1) identify soil and topographic parameters that interact with seeding rate to influence corn grain yield and (2) determine potential soil and topographic parameters that can be used for site-specific optimization of corn seeding rates.

Methods

Experimental design

A field experiment was conducted over three growing seasons (2012–2014) and at three locations in central Iowa, USA to study corn response to seeding rate across landscapes. The fields were located in the Clarion-Nicollet-Webster soil association (Clarion [fine-loamy, mixed, mesic, Typic Hapludolls], Nicollet [fine-loamy, mixed, mesic, Aquic Hapludolls], and Webster [fine-loam, mixed, mesic, Typic Endoaquolls]). The same three sites (Ames, 42°00′50.63″N, −093°44′24.81″W; Kelley, 41°57′09.27″N, −093°41′24.60″W; and Ogden, 42°00′21.55″N, −094°00′49.08″W) were used each of the three years of the experiment in a corn following corn rotation.

The experimental design at each site was a randomized complete block, with four replications at the Ames and Kelley sites and five replications at the Ogden site. Experimental treatments consisted of five seeding rates (61 750, 74 100, 86 450, 98 800, and 111 150 kernels ha^{−1}). These seeding rates were chosen because they bracket the typical seeding rate of 82 000 kernels ha^{−1} used by farmers in Iowa. The plots were 16 rows wide at Ames and Kelley and 12 rows wide at Ogden by field length in a 0.762 m row spacing. Field length was approximately 400 m at Ames and Kelley and 720 m at Ogden.

All field operations were conducted by Iowa State University farm operations staff at the Ames and Kelley sites and the private farm operator at the Ogden site including fall and spring tillage, fertilizer applications, planting, herbicide applications and harvest. At all sites, a disk ripper was used for primary fall tillage and a full width field cultivator (Ames and Kelley) or a rotary harrow (Ogden) for secondary spring tillage. Planting and harvesting equipment was consistent across years (Table 1). Fields at all sites followed typical herbicide and soil fertility programs for phosphorus (P), potassium (K) and pH for the area (Mallarino et al. 2013). A target nitrogen (N) application of 224 kg ha^{−1} was applied as a split application at Ames and Ogden and as single spring pre-plant application at Kelley.

Table 1 Hybrid, planting date, planter model, harvest date and combine model at three central Iowa, USA field experiment sites from 2012 to 2014

Parameter	Ames 42°00'50.63"N, -093°44'24.81"W				Kelley 41°57'09.27"N, -093°41'24.60"W				Ogden 42°00'21.55"N, -094°00'49.08"W			
	2012	2013	2014		2012	2013	2014		2012	2013	2014	
Hybrid	Pioneer P0528XR	Pioneer 1161XR	Pioneer P1023AM		Chanel 209-85VT3Pro	Pioneer 9910XR	Pioneer 34F07		Pioneer 1151HR	Pioneer P0993HR	Pioneer 1360CHR	
Planting date	11 May	18 May	7 May		14 May	14 June	9 May		9 May	14 May	7 May	
Planter	John Deere 7000 with MaxEmerge row units	John Deere 7000 with MaxEmerge row units	John Deere 7000 with MaxEmerge row units		John Deere 7000 with MaxEmerge row units	John Deere 7000 with MaxEmerge row units	John Deere DB60 with MaxEmerge II row units		John Deere DB60 with MaxEmerge II row units			
Harvest date	28 Sept	16 Oct	20 Oct		2 Oct	28 Oct	30 Oct		20 Sept	7 Oct	11 Nov	
Combine	John Deere 9550				John Deere 9550				John Deere 9870			

Different hybrids were planted each site-year resulting in the use of nine hybrids (Table 1). Climatic data was collected from Daymet Software version 2.0 (Thornton et al. 2015) for summation of monthly and growing season precipitation and accumulated growing degree days for each site-year and 30-year means for each site (Tables 2 and 3). Daymet software interpolates and extrapolates daily weather parameters using weather observations distributed by the National Climate Data Center and SNOTEL (SNOWpack and TELelemetry) distributed by the Natural Resources Conservation Service, digital elevation models, algorithms, and computer software to produce 1 km square surface grids.

Field data collection

Sub-plots were established within each replicated seeding rate treatment 30 m apart. At Ames and Kelley, there were 11 sub-plots per strip and at Ogden there were 23 sub-plots per strip. A sub-plot consisted of the center two rows of each strip by 5.3 m long and was staked after planting. Sub-plots were located and marked using an Ashtech MobileMapper 100 (Sunnyvale, CA, USA) with a GNSS antenna that connected to the Iowa Real-Time Network for real-time kinematic global positioning at a 10–20 mm horizontal accuracy. Fourteen soil cores were taken to a depth of 150 mm at the sub-plot level and composite samples were collected between planting and the fourth leaf stage (Abendroth et al. 2011). Soil nutrient and texture analysis was conducted at Midwest Laboratories (Omaha, NE, USA) using standard laboratory procedures. Soil nutrient analysis included P, K, pH, SOM, and cation exchange capacity (CEC) (Dahnke 1975; Kalra 1997; Kuo 1996; Sumner and Miller 1996). The sodium bicarbonate method was used for P (Olsen et al. 1954) and the ammonium-acetate method was used for K (Helmke and Sparks 1996). Available water holding capacity (AWC) was calculated using soil texture and SOM based on Saxton and Rawls (2006).

Grain yield and topographic spatial data

Plots were harvested with combines equipped with calibrated yield monitors and GPS receivers to attain geo-referenced grain yield and moisture information. The harvest width was 9.1 m at Ames and Kelley, where logistically, the center 9.1 m of the 12.2 m seeding rate plot was harvested and the remainder of the plot (four outside rows) was used for collection of ear samples. At Ogden, the harvest width was 9.1 m and the entire plot width was harvested. Yield monitor data were processed and cleaned using Ag Leader Technology SMS Basic (Ames, IA, USA) to ensure start/stop delays, flow shifts, offsets, and erroneous points were omitted before exporting to ArcMap (ESRI 2014). ArcMap was used to determine yield and grain moisture at the sub-plot level by creating 6 or 4.6 m buffers around the central point of the sub-plot followed by a spatial join of the yield information. The buffer distance was half the plot width resulting in yield information for each sub-plot being an average of approximately five to seven yield monitor data points.

Topographic data were generated using 0.61 m contours from the LIDAR 3 m Digital Elevation Model of Boone and Story counties (IA, USA) available from the Natural Resources Geographic Information Systems Library of the Iowa Department of Natural Resources (<https://programs.iowadnr.gov/nrgislibx/>). ArcMap spatial analyst tools were used to determine in-field elevation, slope, curvature, and aspect of each sub-plot. In ArcMap, in addition to slope curvature, planar curvature (curvature perpendicular to the slope) and profile curvature (curvature parallel to the slope) can be determined (ESRI 2014). Positive curvature values result from convex slopes and negative curvature values

Table 2 Monthly and total growing season precipitation at three central Iowa, USA field experiment sites from 2012 to 2014 and the 30-year average precipitation. Precipitation was collected from Daymet Software version 2.0 (Thornton et al. 2015)

Month	Ames				Kelley				Ogden			
	2012	2013	2014	30-year ^a	2012	2013	2014	30-year	2012	2013	2014	30-year
	mm											
April	134	159	176	103	130	162	180	104	123	159	115	99
May	71	267	143	127	73	279	140	131	70	258	132	124
June	82	95	266	139	81	96	265	140	81	107	233	137
July	53	40	91	119	49	40	83	117	30	25	97	114
August	84	32	182	128	87	30	193	128	69	25	162	120
September	59	50	133	84	57	53	135	84	55	40	133	82
Growing season ^b	483	643	991	700	477	660	996	704	428	614	872	676

^a 30-year; average monthly precipitation and average growing season accumulation from 1985 to 2014

^b 1 April to 30 September

Table 3 Monthly and total growing season accumulated growing degree days (10–30 °C) at three central Iowa, USA field experiment sites from 2012 to 2014 and the 30-year average growing degree days. Precipitation was collected from Daymet Software version 2.0 (Thornton et al. 2015)

Month	Ames				Kelley				Ogden			
	2012	2013	2014	30-year ^a	2012	2013	2014	30-year	2012	2013	2014	30-year
	April	128	66	97	104	129	67	99	106	132	65	100
May	272	195	218	212	276	197	220	214	271	193	219	213
June	344	317	333	328	346	320	335	329	344	317	333	328
July	452	376	317	394	454	379	323	397	451	375	318	395
August	348	371	366	362	349	375	370	364	348	370	365	362
September	250	291	220	246	252	294	223	248	249	294	222	247
Growing Season ^b	1793	1615	1551	1647	1807	1633	1569	1658	1796	1613	1556	1651

^a 30-year; average monthly precipitation and average growing season accumulation from 1985 to 2014

^b 1 April to 30 September

result from concave slopes. Slope aspect identifies the direction a slope faces (0 to 360 degrees). For this analysis, slope aspect was transformed to 'northness' with values of -1 to 1 where slope aspects of negative one are more south facing and slopes of positive one are more north facing.

Statistical analysis

Correlation and multiple regression analyses were conducted to understand and identify the key independent variables that best explained corn grain yield (SAS Institute SAS Institute 2012). A stepwise regression procedure was used with $\alpha = 0.05$ for variable addition and deletion in the final model prediction of grain yield. Independent variable collinearity in the regression model was identified using variance inflation factors (VIF). Where VIF of greater than 10.0 was identified, related independent variables were removed from the regression analysis. Collinearity existed between planar and profile curvature which resulted in the use of combined slope curvature. Silt and AWC were removed because collinearity existed between sand, silt, clay, SOM, and AWC. Even with exclusion of independent variables due to VIF greater than 10.0, P, K, SOM, and CEC had a VIF > 10.0 in one, two, four, and two site-years respectively. These variables were important and are common parameters used by farmers and agronomists and therefore retained within the regression and mixed model analysis.

The optimum seeding rate was estimated using a model where corn grain yield was the dependent variable. The initial model, included the effects of replication, seeding rate, seeding rate squared, identified soil and topographic parameters plus the seeding rate interaction with the soil and topographic parameters. A reduced model was then fit by excluding non-significant seeding rate interactions with soil and topographic variables. It was considered whether to include spatial dependence among residuals by fitting models with spatially correlated residuals. Gaussian and exponential covariance structures were computed from the X, Y coordinates of each sub-plot. The correlation between each pair of sub-plots depended on their Euclidean distance. None of the nine site-years showed evidence of spatial dependence in the residuals because the soil and topographic independent variables included in the mixed model accounted for the geographic dependence of the sub-plots.

Optimum seeding rates (SR_{opt}) at each sub-plot were determined by solving the model for maximum seeding rate:

$$Yield = \beta_0 + \beta_1 SR + \beta_2 SR^2 + \beta_3 (\text{var} \times SR) \quad (1)$$

$$Yield = \beta_0 + (\beta_1 + \beta_3 \text{var}) SR + \beta_2 SR^2 \quad (2)$$

SR_{max} solves Eq. 2

$$\frac{dYield}{dSR} = \beta_1 + \beta_3 \text{var} + 2\beta_2 SR_{max} = 0 \quad (3)$$

$$SR_{opt} = SR_{max} = \frac{-(\beta_1 + \beta_3 \text{var})}{2\beta_2} \quad (4)$$

where Yield is the corn grain yield, SR is the seeding rate, var represents those soil attributes or topographic characteristics that interact with seeding rate, SR_{max} is the seeding rate at which the highest yield can be expected, SR_{opt} is the optimum seeding rate for the sub-plot based on the derivatives of corn grain yield, seeding rate, and significant seeding

rate \times variable interactions. The PROC MIXED procedure in SAS was used for the optimum seeding rate computations.

Results and discussion

Field variability assessment

Descriptive statistics revealed a significant amount of variability in soil properties and topographic characteristics across and within sites, with coefficient of variation (CV) values generally greater than 15 % (Tables 4, 5; Fig. 1). This amount of variability was desired for the purpose of the experiment and sites were selected based on perceived and known variability.

Mean grain yields across site-years were highly variable ranging from 10.4 to 12.7 Mg ha⁻¹ with CV values ranging from 5.3 to 33.2 % (Table 4; Fig. 2). The greatest within-site corn yield variability was at Ames in 2013 which can be attributed to large variation in topographic characteristics combined with greater than normal precipitation following planting causing reductions in stand establishment in field depressions (results not shown). While the Kelley site in 2013 exhibited low corn grain yield variability, it too experienced greater than normal precipitation in April and May which resulted in a mid-

Table 4 Descriptive statistics of grain yield and selected soil nutrient parameters at three central Iowa, USA field experiment sites from 2012 to 2014

Parameter ^a	Year	Ames			Kelley			Ogden		
		Mean	Range	CV (%)	Mean	Range	CV (%)	Mean	Range	CV (%)
Grain yield, Mg ha ⁻¹	2012	12.2	4.8–15.4	12.6	11.3	5.8–13.7	11.8	12.7	5.1–16.2	13.9
	2013	10.4	0.4–13.3	33.2	10.7	6.4–12.3	8.8	10.8	0.9–16.0	17.4
	2014	11.6	5.6–14.1	12.0	11.0	2.1–13.8	20.7	12.3	10.4–14.4	5.3
P, mg kg ⁻¹	2012	11	6–18	23.4	23	11–86	52.6	15	5–72	55.7
	2013	12	5–47	47.1	28	9–74	42.4	17	5–81	58.8
	2014	14	4–66	50.1	26	9–61	37.4	19	5–68	50.4
K, mg kg ⁻¹	2012	170	120–224	15.9	224	176–412	18.9	185	93–369	29.4
	2013	173	108–292	20.3	233	124–389	22.5	211	114–509	25.2
	2014	166	85–281	18.9	216	128–381	20.6	196	85–470	29.8
pH	2012	6.5	5.3–7.9	12.5	5.9	5.2–7.2	7.7	7.0	4.6–8.1	12.6
	2013	6.2	4.7–8.1	17.0	5.9	4.5–7.9	14.0	6.8	4.6–8.1	14.7
	2014	6.2	4.6–8.1	17.5	5.9	4.7–8	14.5	6.7	4.5–8.1	15.6
CEC, cmol kg ⁻¹	2012	23.1	12.2–37.6	31.5	24.9	15.8–33.3	15.2	26.9	17.1–42.7	20.3
	2013	24.2	13.2–35.5	25.6	24.9	14.3–35.6	19.1	27.7	14.9–38.2	18.3
	2014	25.6	12.3–41.5	27.1	26.2	13.8–38.7	21.0	26.6	13.2–43.1	21.6
OM, g kg ⁻¹	2012	40	14–68	36.5	34.5	22–57	18.0	42	24–86	27.6
	2013	39	11–69	39.6	32.7	13–64	25.7	44	21–86	24.6
	2014	45	15–78	35.8	38.7	18–65	21.8	47	22–95	24.3

^a P phosphorus, K potassium, CEC cation exchange capacity, OM organic matter

Table 5 Descriptive statistics of selected soil and topographic parameters at three central Iowa, USA field experiment sites

Parameter	Ames			Kelley			Ogden		
	Mean	Range	CV (%)	Mean	Range	CV (%)	Mean	Range	CV (%)
	Sand, g kg ⁻¹	456	220 to 620	16.0	482	300 to 620	11.7	425	200 to 620
Clay, g kg ⁻¹	223	160 to 340	16.2	215	120 to 320	15.7	235	80 to 500	21.2
Slope, degrees	8.5	0.3 to 31.3	67.5	6.7	0.4 to 21.7	61.6	5.2	0.1 to 15.9	60.0
Curvature ^a	-0.02	-5.09 to 3.42	n/a	0.06	-1.10 to 1.57	n/a	-0.04	-3.39 to 2.47	n/a
Aspect ^b	0.32	-1.00 to 1.00	n/a	-0.10	-1.00 to 1.00	n/a	0.03	-1.0 to 1.0	n/a
Elevation, m ^c	323	320 to 328	0.5	314	313 to 316	0.2	332	330 to 334	0.3

^a Slope curvatures are convex when positive and concave when negative

^b Aspect transformed to 'northness' where 1 equals north facing slopes and -1 equals south facing slopes

^c Above sea level

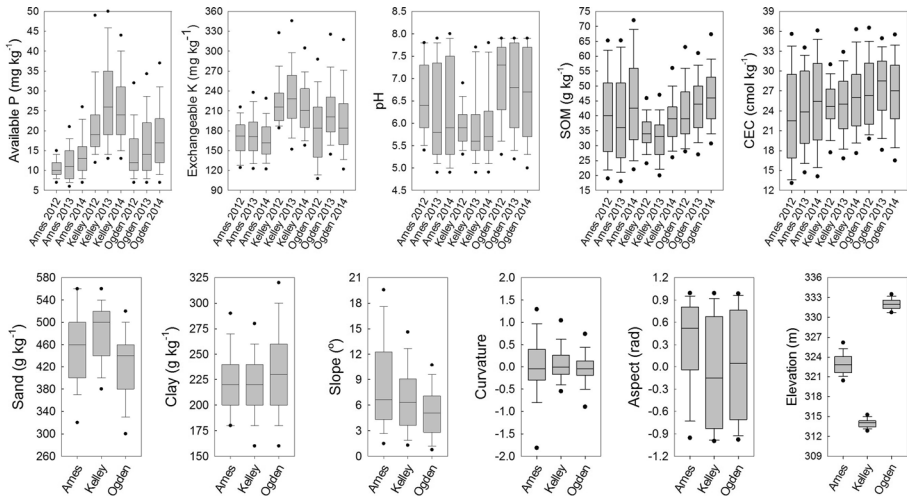


Fig. 1 Descriptive statistics of the soil variables and topographic characteristics of Ames, Kelley, and Ogden in central Iowa in 2012, 2013, and 2014. Median, line within the box; 25/75th percentile, box; 10/90th percentile, whiskers; 5/95th percentile, black dot

June planting date. Therefore, this site had less stand reduction due to saturated soil conditions than the other sites in 2013.

Corn yields were the highest in 2012 and the lowest in 2013 (Table 4). Kelley was the lower yielding site and Ogden was the higher yielding site. The annual corn yield variability can be attributed to climatic conditions: 2012 was extremely dry; 2013 was cool and wet in April and May, followed by dry conditions; and 2014 was cool and wet throughout the growing season (Tables 2, 3).

Correlation and regression analysis

Seeding rates and corn grain yield were correlated in seven of nine site-years. In six of these seven site-years, corn grain yields were negatively correlated with seeding rate (Table 6). Soil fertility parameters were inconsistently correlated with corn grain yields across site-years. In the abnormally dry year of 2012, slope, curvature and in-field elevation were negatively correlated with corn yield. Additionally, SOM and clay content were positively correlated with grain yield. In totality, the combination of these parameters suggest that water availability and storage are important parameters in determining yield potential and an optimal seeding rate for specific areas within fields, especially in years with dry weather conditions. Conversely, in 2013 and 2014, curvature and in-field elevation each were positively correlated with corn grain yield while clay and sand content were not consistently correlated with grain yield. Positive grain yield correlation with slope, curvature, and in-field elevation indicate that while the ability to capture and store water in a dry year is beneficial, in wet years a more variable topography results in water dispersion from the summit and hillslope landscape positions, and results in higher corn yields. The influence of soil water drainage and storage on grain yields have been well known but are highly inconsistent depending on soil type, topography, and climatic

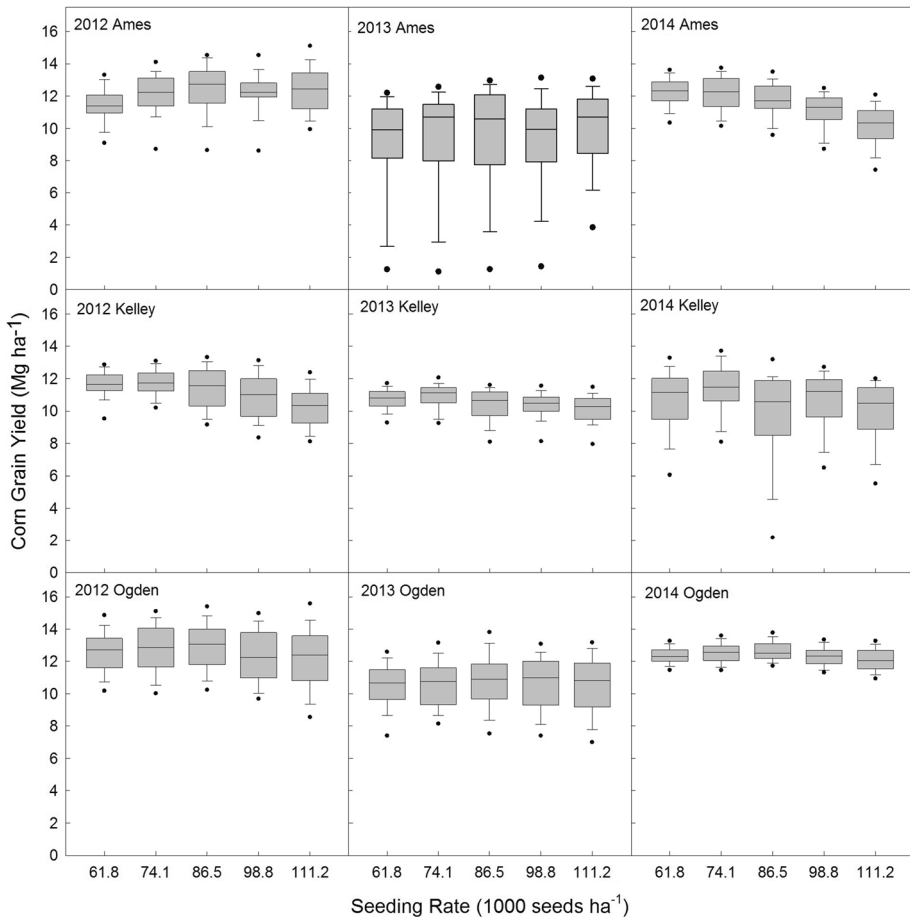


Fig. 2 Corn grain yield descriptive statistics by seeding rate for Ames, Kelley, and Ogden in 2012 to 2014. Median, line within the box; 25/75th percentile, box; 10/90th percentile, whiskers; 5/95th percentile, black dot

conditions of the research sites (Kaspar et al. 2004; Kravchenko and Bullock 2000; Runge and Hons 1999; Spitze et al. 1973).

Generally, the step-wise regression models reflect the correlation coefficients for each site-year (Table 7). The highest coefficients of determination (R^2) for the regression model analysis were at the Ames site with an R^2 of 0.65 and 0.77 in 2012 and 2014 respectively. The lowest R^2 values were at Kelley in 2013, Ogden in 2012, and Ames in 2013, $R^2 = 0.16$, 0.17, and 0.20 respectively. Regression analysis included seeding rate and/or seeding rate squared in all site-years except Ames in 2013. In most situations, the seeding rate and seeding rate squared parameters were negative and extremely low, indicating little influence of seeding rate on the yield prediction.

In both Ames and Kelley, the regression model R^2 values were much lower in 2013 compared to 2012 and 2014. These lower R^2 values can be attributed to areas of the field that had reduced plant densities and yield due to saturated soil conditions early in the year

Table 6 Significant Pearson correlation coefficients of corn grain yield to soil and topographic parameters, 2012–2014

	Ames			Kelley			Ogden		
	2012	2013	2014	2012	2013	2014	2012	2013	2014
Seeding rate	0.17**	ns	-0.55***	-0.38***	-0.27***	-0.15*	-0.10*	ns	-0.16***
P	0.55***	ns	-0.22**	0.27**	ns	-0.34***	0.15**	ns	0.43***
K	0.63***	ns	ns	0.30***	ns	-0.29***	ns	-0.26***	0.31***
pH	ns	-0.29***	-0.70***	Ns	ns	-0.44***	0.09*	-0.26***	-0.40***
SOM	0.46***	-0.29***	-0.50***	0.36***	ns	-0.42***	0.19***	-0.37***	0.09*
CEC	0.43***	-0.33***	-0.42***	0.40***	ns	-0.33***	0.10*	-0.27***	ns
Sand	-0.52***	0.13*	ns	Ns	ns	ns	-0.19***	ns	ns
Silt	0.46***	ns	-0.14*	Ns	ns	ns	0.19***	-0.11**	ns
Clay	0.22**	ns	0.16*	Ns	ns	ns	0.09*	ns	ns
Slope	-0.46***	0.24**	0.27***	-0.20**	ns	0.18**	-0.19***	0.28***	-0.09*
Curvature	-0.19**	ns	ns	-0.34***	ns	0.44***	-0.14**	ns	ns
Aspect	ns	ns	-0.29***	0.16*	ns	ns	-0.16**	0.11**	-0.14**
Elevation	-0.58***	0.24**	0.39***	-0.24**	ns	0.44***	-0.31***	0.53***	ns

Minimum and maximum number of observations for the correlation parameters: Ames-2012, n = 187–220; Kelley-2012, n = 180–220; Ogden-2012, n = 352–554; Ames-2013, n = 193–220; Kelley-2013, n = 220; Ogden-2013, n = 553–554; Ames-2014, n = 219–220; Kelley-2014, n = 220; Ogden-2014, n = 552–554

ns not significant

* Significant at the 0.05 probability level; ** Significant at the 0.01 probability level; *** Significant at the 0.001 probability level

Table 7 Regression models for predicting corn grain yields using seeding rate (rate and rate squared), soil parameters, and topographic characteristics. All models were significant at the 0.0001 probability level

Site-year	Regression model ^a	Model R^2
Ames, 2012	$Y = 135.76 + 1.35e^{-5}\text{Rate} - 8.69e^{-10}\text{Rate}^2 + 0.05 \text{ K} + 0.15\text{pH} - 0.02\text{SOM} - 0.14\text{CEC} - 6.06e^{-3}\text{SD} - 0.02\text{CL} - 0.07\text{SL} - 0.37\text{E}$	0.65
Ames, 2013	$Y = 19.76 + 0.01 \text{ K} - 0.35\text{pH} - 0.17\text{CEC} - 0.01\text{SD} - 0.01\text{CL} - 0.05\text{SL} - 0.25\text{C}$	0.20
Ames, 2014	$Y = 17.54 - 3.90e^{-5}\text{Rate} - 4.02e^{-10}\text{Rate}^2 - 0.01\text{P} + 0.01\text{K} - 0.77\text{pH} + 0.01\text{SOM} - 0.07\text{CEC} - 9.45e^{-4}\text{SD} - 0.02\text{SL}$	0.77
Kelley, 2012	$Y = 93.73 - 2.93e^{-5}\text{Rate} - 0.03\text{P} + 0.01 \text{ K} - 0.68\text{pH} + 0.16\text{CEC} - 8.86e^{-3}\text{CL} + 0.05\text{SL} - 0.34\text{C} + 0.49\text{A} - 0.27\text{E}$	0.50
Kelley, 2013	$Y = 85.04 - 1.37e^{-5}\text{Rate} - 2.37e^{-10}\text{Rate}^2 - 0.01\text{P} + 2.34e^{-3}\text{K} - 0.24\text{pH} + 0.03\text{CEC} - 2.54e^{-3}\text{CL} + 0.04\text{SL} - 0.23\text{E}$	0.16
Kelley, 2014	$Y = -193.34 - 2.07e^{-5}\text{Rate} - 0.01 \text{ K} - 0.90\text{pH} + 0.06\text{CEC} - 0.01\text{SD} - 0.01\text{CL} + 1.60\text{C} - 0.28\text{A} + 0.68\text{E}$	0.41
Ogden, 2012	$Y = 186.85 - 8.87e^{-6}\text{Rate} - 7.95e^{-10}\text{Rate}^2 + 0.03\text{P} - 7.76e^{-3}\text{K} - 5.66e^{-3}\text{SD} - 0.06\text{SL} - 0.33\text{C} - 0.26\text{A} - 0.51\text{E}$	0.19
Ogden, 2013	$Y = -333.64 - 4.32e^{-10}\text{Rate}^2 + 0.01\text{P} - 4.91e^{-3}\text{K} + 1.56e^{-3}\text{SD} + 4.64e^{-3}\text{CL} + 0.06\text{SL} - 0.19\text{C} + 1.03\text{E}$	0.32
Ogden, 2014	$Y = 69.85 - 6.21e^{-6}\text{Rate} - 6.23e^{-10}\text{Rate}^2 + 0.02\text{P} - 0.30\text{pH} + 0.01\text{CEC} - 0.02\text{SL} + 0.07\text{C} - 0.08\text{A} - 0.17\text{E}$	0.39

Y corn grain yield (Mg ha^{-1}), Rate seeding rate (seeds ha^{-1}), P phosphorus (mg kg^{-1}), K potassium (mg kg^{-1}), SOM soil organic matter (g kg^{-1}), CEC cation exchange capacity (cmol kg^{-1}), SD sand (g kg^{-1}), CL clay (g kg^{-1}), SL silt (g kg^{-1}), C curvature, A aspect (radians), E elevation (m)

^a Regression models derived from each site-year data set

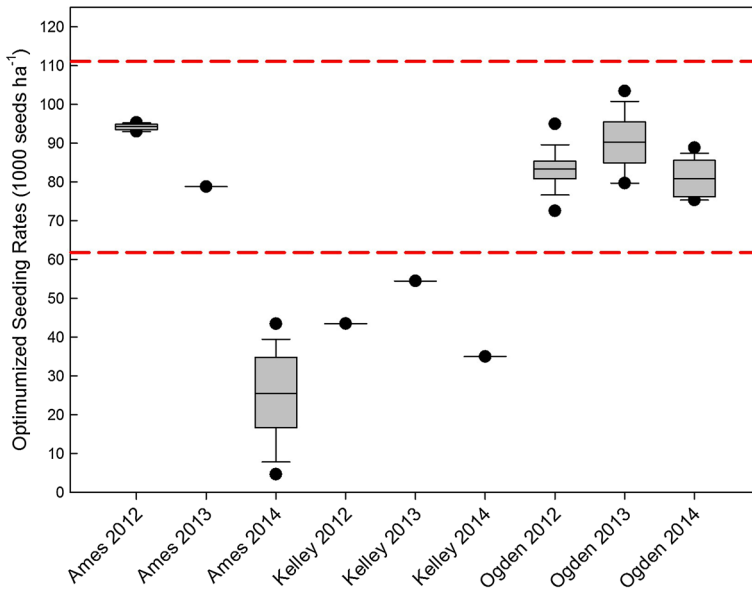


Fig. 3 Range of optimized seeding rates for each sub-plot of each site-year from central Iowa. Median, line within the box; 25/75th percentile, box; 10/90th percentile, whiskers; 5/95th percentile, black dot; dashed line indicates upper and lower seeding rate treatment used

and dry conditions that were detrimental to grain production during grain fill later in the season. Therefore, most of the parameter coefficients in the regression model were low and therefore had little effect on the yield prediction.

Seeding rate optimization

The focus of this work was to determine if there is a way to use known field characteristics combined with seeding rate treatments and yield outcomes to determine optimum seeding rates for future plantings based on those known field characteristics. The results showed that in four site-years (Ames 2013 and Kelley 2012, 2013, and 2014) there was no optimized seeding rate due to a lack of a seeding rate interactions with soil parameters and topographic characteristics (Fig. 3). This does not mean soil parameters or topographic characteristics do not influence corn grain yields. It does mean that the optimization of seeding rates was not affected by the selected field characteristics.

Five site-years had a seeding rate interaction with a soil parameter(s) and/or topographic characteristic(s). Of the five site-years, Ames 2014 had optimum seeding rates below the range of corn seeding rate treatments used in the experiment, thus limiting the validity and usefulness of the seeding rate optimization analysis for this site-year. This is very likely due to low coefficient estimates for seeding rate interactions with pH, CEC, and SOM combined with essentially no coefficient estimate for seeding rate squared ($-2.84e^{-10}$). In Ames in 2014, the seeding rate response curve across the field had a narrow range of peak yields between the 61 750 and 74 100 seeds ha^{-1} seeding rates.

Four site-years (Ames 2012 and Ogden 2012, 2013, 2014) provided corn seeding rate optimizations that fell within the range of seeding rate treatments used in the experiment,

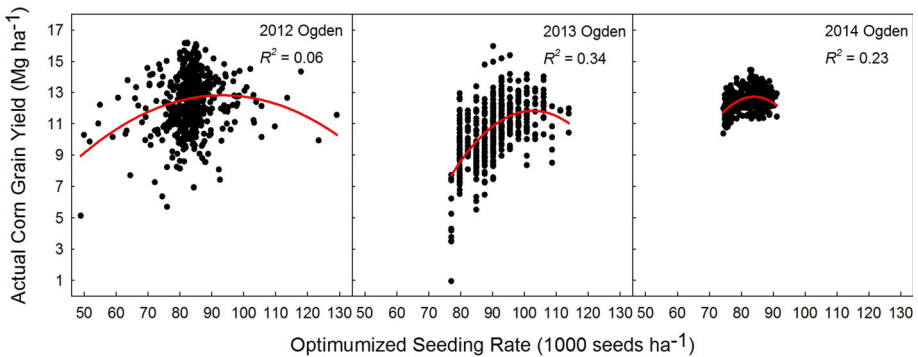


Fig. 4 Corn grain yield at the optimized seeding rate for each sub-plot for Ogden in 2012–2014

three of which provided a range of optimum seeding rates large enough to develop a dynamic seeding rate response curve (Fig. 4). The Ames 2012 optimum seeding rates ranged from 92 950 to 95 430 seeds ha^{-1} while the Ogden site had mean optimum seeding rates of 83 270, 90 680, and 81 020 seeds ha^{-1} in 2012, 2013, and 2014, respectively. The Ogden site-year seeding rate response curves match up to seeding rate response curves used as the basis for corn seeding rate recommendations that maximize yields (Hoeft et al. 2000; Mueller and Sisson 2013; Nafziger 2012; Nielsen et al. 2015; Woli et al. 2014).

Conclusions

The site years of this study proved not only to have large variability of soil and topographic parameters but also considerable corn grain yield and optimum seeding rate variability. Individual sites exhibited different corn yield and seeding rate responses due in part to differences in field variability. Slope, curvature, in-field elevation, and SOM were commonly correlated with corn yield in dry climatic conditions of 2012. When the planting and growing season had normal to cool/wet conditions, corn yield correlations to variables were less consistent. Regression models for all site-years were inconsistent in the amount of yield variability accounted for by the soil and topographic variables (16–77 %).

When seeding rate optimization was performed, only three of nine site-years resulted in meaningful seeding rate response curves that warranted use of variable seeding rates across fields. Even in those site-years, there was considerable variation of the optimization model. These findings support the hypothesis that for variable rate seeding to be viable there is a need for seeding rate to be influenced by soil attributes and topographic characteristics with an additional need for consistency of seeding rate interaction with soil attributes and topographic characteristics from year to year and field to field.

Determining a single optimum seeding rate methodology based on soil and/or topographic variables across a farming operation seems unlikely due to seeding rate response and interactions with variability of climatic conditions and field characteristics. Based on this study, further research needs to be conducted to better understand how seeding rate optimization can be accomplished effectively. Development of seeding rate response curves for individual management zones based on indices that account for the influence of

soil fertility, water holding capacity, and landscape position on seeding rate response curves would be of great value.

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