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Economic Optimum Plant Density for Maize Under Irrigation in Texas

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Summary

The economic optimum plant density (EOPD) for maize can be considered a function of gross economic return on grain yields minus the variable input cost of seed.

We determined the EOPD for irrigated maize under three soil temperature regimes in Texas by measuring grain yield of four maize hybrid entries under increasing plant densities. The population study was performed at five locations over four growing seasons from 2004 through 2007 on soils classed as mesic, thermic and hyperthermic.

Analysis was performed in five stages:

1. aggregated grain yield and economic returns were tested for parameter interactions;
2. maximum grain yield response to increasing plant density was estimated by fitting a quadratic function to plant density versus grain yield response for each hybrid entry by site and year (63 hybrid site years);
3. quadratic function was developed to estimate the plant population density corresponding to the maximum economic return for each of nine economic scenarios, where grain yield was assigned three assumed values to establish gross return and three assumed seed costs to establish relative economic net returns;
4. grain yield was calculated using the quadratic models from Step 2 and population data developed from the economic scenarios in Step 3 to create simple linear economic optimum plant density models, one for each of region and economic scenario (27 linear regression models); and
5. interactive decision tool was created using the linear models from Step 4 to assist irrigated maize producers with agronomic planning by indicating the economic optimum plant density by region, where input parameters are irrigated maize yield goal, seed cost and grain value.

Analytical results, model development process, and model interface are presented.

Introduction

Decades of research on a multitude of maize phenotypes clearly indicates that plant density impacts maize grain yields (Hunter 1969, Cox 1977, Norwood 2001, Liu 2004, Hashemi 2005, Sarlangue 2007). Stalk lodging has been shown to be the principal factor restricting the adoption of higher plant densities, followed by stalk barrenness, and reduced ear and kernel sizes (Stanger 2007). The introduction of transgenic varieties, (e.g., Yield Guard, Bt, Roundup Ready, etc.) and improvements in stalk strength have enhanced stalk lodging resistance and facilitated the more recent adoption of even higher plant population densities.

Environmental factors such as pre-season soil moisture, growing degree day accumulation rates, evening air temperatures (Peters 1971), and the frequency and duration of growing season precipitation typically reduce grain yields below their potential. In Texas, irrigation water is applied to supplement precipitation and is in most years, the driving force needed to realize positive economic returns. Other intensive management techniques such as optimized fertility programs and seeding at higher population densities have little effect without adequate moisture.

There are few reports on determinations of economic optimum plant density for irrigated maize, where the economic optimum plant density (EOPD) for maize is considered a function of gross economic return on grain yields minus the variable input cost of seed. Most efforts to address this topic analyzed maize plant population densities under rain-fed conditions where sporadic precipitation events imposed significant confounding effects on their observations (Bullock 1998, Popp 2006, Stranger 2006).

This study was conducted to determine the economic optimum population plant densities for irrigated maize under a range of climate conditions across Texas, where environmental factors vary considerably from south to north and east to west. Extreme conditions commonly observed during periods of maize production impose significant limitations on maize grain yields, and on plant density optimization research. For example, South Texas irrigated maize production is severely limited by high night air temperatures, low relative humidity, significant deficits of pre-season soil moisture, and severe disease and pest pressures. The central region has fewer limitations, less severe pest and disease pressures, higher pre-season soil moisture reserves, and somewhat cooler evening temperatures and higher relative humidity. Limitations associated with North Texas irrigated maize production are minimal which explains why record high grain yields are common in that region of the state.

Materials and Methods

Irrigated maize hybrid grain yield response to increasing plant density (plants ha^{-1}) was evaluated in three soil temperature regimes of Texas. The experimental design at each site and year was a complete factorial randomized complete block with four replications, and included four hybrid entries and five to six plant populations. The study was replicated across five locations and four growing seasons. Cropping conditions of the locations were representative of the respective regions, with two study sites in the High Plains of North Texas on soils classed as mesic; one site in Central Texas on a soil classed as thermic; and two sites in South Texas on soils classed as hyperthermic, with the exception of one site in 2006 which was on a soil classed as thermic. Refer to Table 1 for complete soil taxonomic classifications.

Table 1. Soil taxonomic classifications.

Sites	Year	Soil Series	Taxonomic Classifications
1, South	2005-07	Raymondville clay loam	Raymondville fine, mixed, superactive, hyperthermic vertic calciustolls
2, South	2005	Castroville clay loam	Castroville fine-silty, carbonatic, hyperthermic typic calciustolls
2, South	2006	Knippa clay	Knippa fine, mixed, superactive, thermic vertic calciustolls
2, South	2007	Victoria clay	Victoria fine, smectitic, hyperthermic sodic haplusterts
3, Central	2005-07	Ships clay loam	Ships very-fine, mixed, active, thermic chromic hapluderts
4, North	2004-07	Dallam sandy loam	Dallam fine-loamy, mixed, superactive, mesic aridic paleustalfs
5, North	2004-07	Sherm silty clay loam	Sherm fine, mixed, superactive, mesic torrertic paleustolls

Four maize hybrid entries (H1: Garst 8292 YG1, H2: Golden Acres 2840 BT, H3: Triumph 1866 BT, and H4: Garst 8377 YG1RR) were selected for their average or above average historical performance (Table 2). The project was initiated in 2004 at two locations with collaborating producers in North Texas, Dumas and Dalhart, where the four hybrids were evaluated under five population densities (41,990; 54,340; 66,690; 81,510; and 91,390 plants ha^{-1}).

The experiment was expanded to include four additional locations in 2005, 2006 and 2007, with the same four hybrid entries, with six plant densities (41,990; 54,340; 66,690; 79,040; 91,390; and 103,740 plants ha^{-1}) at the north Texas locations, and five plant densities (41,990; 54,340; 66,690; 79,040; and 91,390 plants ha^{-1}) at the central and south Texas locations.

Experimental plots were fertilized according to soil test recommendations and collaborating producers' management programs. Weed and insect pest control was also successfully managed by the collaborating producers. Irrigation schedules varied by year and site, and were altered by the collaborating producers as needed to supplement precipitation. Plots were planted at the specified treatment plant densities using cones mounted on an ALMACO planter equipped with John Deere Max-Emerge II planter units.

Table 2. Hybrid entries (H1 – H4). Transgenic maize hybrid traits include corn borer resistance (YG1), glyphosate resistance (RR), Lepidopteron resistance (BT, B), and root worm resistance (W).

	Company	Hybrid	GMO Trait	Year included
H1	Garst	8292	YG1	2004, 2005
H1	Garst	8295	YG1/RR	2006, 2007
H2	Golden Acres	2840	BT	2004
H2	Golden Acres	2842	RRBW	2005 – 2007
H3	Triumph	1866	BT	2004 – 2007
H4	Garst	8377	YG1/RR	2004 – 2007

Harvest grain yield and grain moisture were gathered from the center two rows of four-row plots with a John Deere 3300 plot combine equipped with a grain gauge, where the plot harvest dimension for the Site 1 (WESLACO) was a 2-row spacing of 1.016 m × a length of 7.62 m, Site 2 (CASTROVILLE) 0.914 m × 7.62 m, Site 3 (COLLEGE STATION) 0.762 m × 6.40 m, Site 4 (DALHART) 0.762 m × 7.62 m, and Site 5 (DUMAS) 0.762 m × 7.62 m. Harvested grain yields were adjusted to 155 g kg^{-1} water content.

Data Analysis

Statistical analysis was performed in five steps with JMP® Statistical Discovery Software v.7.0.2 (SAS Institute Inc., Cary, NC).

Step 1: Overall Statistical Analysis. Second order Factorial Analysis was performed by Standard Least Squares to evaluate the fixed effect of increasing plant density (PD) on maize grain yields, accounting for the random effects of hybrid entries (HE), multiple years (Y), sites (S), and replication blocks (B). Outlier analysis was performed with Jackknife distances on fixed effect parameters (grain yield versus plant density) by hybrid entry, site and year. Fixed Effect Tests (mixed model) of the Restricted Maximum Likelihood (REML) Analysis revealed numerous statistically significant interactions, which were accounted for in subsequent steps by evaluating yield and economic response models for each HE × Y × S to produce 63 response curves for PD at maximum yield (Step 2), and PD for each of 9 maximum economic return scenarios (Step 3), where B effects and B × PD interactions are included as part of the model (Table 3).

Step 2: Maximum yield response to increasing plant density. Standard Least Squares analysis was used to generate a predictive quadratic response model for each hybrid entry to determine the plant density at maximum grain yield for each of the four hybrid entries by year and location. Significantly different effects by study site as revealed in REML from Step 1, were accounted for by grouping site data by dominant soil temperature regime as described into three groups, North (N), Central (C) and South (S). Refer to Table 1. Maximum yield response data for each of the 45 responsive entries were regressed against their corresponding plant density within each of the three regions to develop three optimization models for maximum yield plant density. Twenty eight of the 63 quadratic models were identified as either non-responsive by their lack of inflection (positive squared term) and poor fit where response was statistically the same as the mean with a p-value greater than 0.20 or identified as an outlier and excluded from further analysis (data not shown).

Step 3: Determine economic optimum plant densities for each hybrid entry by site and year. A quadratic model including block effects and an interaction term for B × PD was developed for each responsive entry for each of nine economic net return scenarios by region where we assume variable seed costs of $120, $160, and $200 per 80,000 seeds, and variable grain values of $80, $200 and $315 per Mg of grain. Economic net return was calculated for each grain yield observation by multiplying moisture-corrected grain yield by grain value and subtracting seed cost. The plant density corresponding to the maximum economic return for each of the nine economic scenarios was determined with procedures described in Step 2 for maximum grain yields.

Step 4: Develop a linear EOPD regression model for each of the nine economic scenarios and three regions (27 regression models). The agronomic grain yield for each responsive hybrid entry was back calculated from the economic optimum plant densities as determined in Step 3 using the corresponding hybrid entry yield response models developed in Step 2. Agronomic grain yields of the 45 responsive trials were regressed against their corresponding plant densities by region to develop three optimization models to yield optimal plant density by maximum yield for each of the 27 economic scenarios. (Refer to Fig 2).

Step 5: An interactive EOPD calculator was created in MS Excel using models developed in Step 4 where the upper and lower bounds for plant density, seed cost and grain value were imposed to reflect our economic analysis cost and value assumptions. Yield goal upper and lower bounds are varied by region of the state reflecting our observed average minimum and maximum grain yields for each of the three regions.

Table 3. REML Analysis for grain yield response to increasing plant density (PD, fixed effect), with hybrid entries (HE) over years (Y) study sites (S) and replication blocks (B) as random effects.

	R^2	R^2 Adj	RMSE	Mean	Obs
Summary of Fit	0.82	0.81	1.338	11.530	1168

REML Variance Component Estimates

Random Effect	Variance Ratio	Variance Component	Standard Error	95% Lower	95% Upper	Percent of Total
S (Site)	2.267	4.058	3.233	-2.279	10.396	46.6
Y (Year)	0.642	1.150	1.385	-1.563	3.864	13.2
B (Block)	-0.009	-0.016	0.009	-0.034	0.002	-0.2
HE (Hybrid Entry)	0.030	0.054	0.072	-0.088	0.196	0.6
S × Y	0.836	1.496	0.742	0.042	2.951	17.2
S × B	0.006	0.010	0.018	-0.025	0.045	0.1
S × HE	0.067	0.120	0.064	-0.006	0.245	1.4
Y × B	0.024	0.043	0.032	-0.019	0.106	0.5
Residual		1.790	0.077	1.649	1.951	20.6
Total		8.707				100.0

Fixed Effect Tests (mixed model)

Source	Nparm	DF	DFDen	F Ratio	Prob > F	
PD (Plant Density)	1	1	1086	303.131	< 0.0001	***
S × PD	4	4	1086	16.269	< 0.0001	***
Y × HE	9	9	1055	3.570	0.0002	***
Y × PD	3	3	1087	22.864	< 0.0001	***
B × HE	9	9	1101	1.369	0.1975	
B × PD	3	3	1089	1.231	0.2971	
HE × PD	3	3	1095	18.254	< 0.0001	***

Level of statistical significance, where p-value ≤ 0.01 (***), ≤ 0.05 (**), ≤ 0.10 (*)

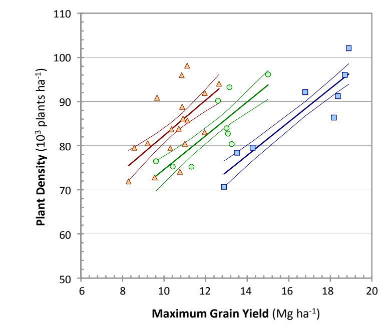
Results and Discussion

Average grain yields were highest for sites in the north region, followed by moderate grain yields for the central region site, and lowest for sites in the south region. ANOVA analysis indicates a statistically significant difference across regions and locations (Table 4).

Grain yield response to increasing plant density varied by region, where small increases in grain yields per incremental change in plant density were observed in the southern region versus correspondingly larger increases in grain yield in the central and north regions (Fig 1). This difference in response rate is attributed to small ear size and fewer numbers of kernels per ear that occur on hyperthermic soils in South Texas. Tests for differences across groups using Least Squares Means Differences Student's t, where alpha = 0.10 and t = 2.03, revealed significant differences in maximum yield plant densities (PD) and economic net return across climate regions (Fig 1 inset).

Table 4. Average grain yields by region, site and year. Mean separation was determined by student's t for each of two ANOVA classification variables (region and site). Levels within each class not connected by the same letter are significantly different, where α = 0.05 and p < 0.05.

Region	Site	Year	Mean	±	Std Dev	CV%	Obs
NORTH (a)	Dumas (b)	2004	13.11	±	1.66	13%	60
		2005	10.75	±	1.41	13%	63
		2006	12.10	±	1.38	11%	71
	Dalhart (a)	2004	16.73	±	1.82	11%	59
		2005	14.71	±	1.73	12%	87
		2006	11.77	±	2.22	19%	93
		2007	16.38	±	2.28	14%	86
CENTRAL (b)	College Station (c)	2005	9.44	±	1.33	14%	71
		2006	11.46	±	2.03	18%	69
		2007	11.95	±	2.40	20%	55
SOUTH (c)	Castroville (d)	2005	9.27	±	1.09	12%	80
		2006	9.36	±	1.34	14%	78
		2007	10.58	±	1.44	14%	76
	Weslaco (e)	2005	9.89	±	1.11	11%	78
		2006	7.17	±	1.05	15%	63
		2007	9.56	±	1.28	13%	79



Regions	Slope	Intercept	R^2	p-value	LS Means Differences (PD) Student's t (α = 0.10)	
NORTH	3,782	24,839	0.81	***	69,561	A
CENTRAL	3,828	36,326	0.60	***	84,908	B
SOUTH	4,000	42,331	0.31	***	95,787	C

Fig 1. Plant density versus maximum yield by region. Site response data was grouped by temperature regime, where mesic sites are labeled as NORTH, thermic as CENTRAL, and hyperthermic as SOUTH. The linear relationship for each region is illustrated with a color-coded line of the linear model bounded by model standard error (refer to table inset). The ANOVA test revealed an overall adjusted R^2 of 0.65 and p-value less than 0.0001.

Figure 2 illustrates variable seed costs and grain values on optimal plant densities. As seed costs and grain values increase, the magnitude of change in EOPD decreases. This relationship is most apparent when yield goals exceed 11.5 Mg ha^{-1}, and most pronounced for the North region where relatively small incremental changes in plant density were observed to affect significant increases in grain yields.

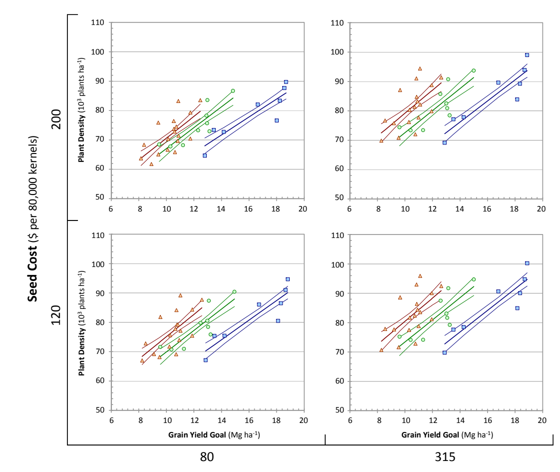
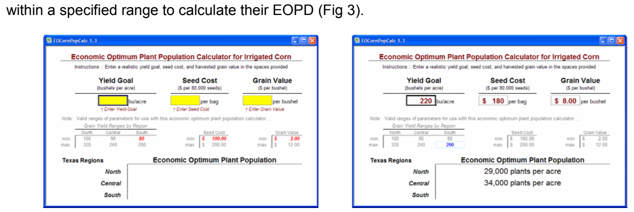


Fig 2. Economic optimum plant density (EOPD) versus yield goal by region. Nine economic scenarios were evaluated for each region, while four scenarios are presented in this figure. The slope, intercept and R^2 for each of the economic scenarios were determined for each of three regions (soil temperature regimes).

Economic Optimum Plant Density Models

The three linear models presented in Figure 1 (NORTH, CENTRAL, and SOUTH) could be used to calculate plant densities needed to achieve maximum grain yield. The EOPD models consider three variables: grain yield goal, seed cost, and grain value. EOPD slope and intercept coefficients were found to vary independently with increasing seed costs and grain values (data not shown). To leverage the linear trends of the linear relationships, the EOPD model was expanded by applying Standard Least Squares regression analysis to generate EOPD slope and intercept coefficients by region for seed cost and grain value. The expansion of the models (Fig 1) provided the coefficients needed to create an interactive tool where a user can input any yield goal, seed cost or grain value within a specified range to calculate their EOPD (Fig 3).



Calculator interface. Three data entry fields are colored yellow. Note editable min and max model limits for grain yield, seed cost and grain value.

Output. EOPD is displayed for two regions. Note that the specified yield goal exceeds the upper bound for south region.

Fig 3. Product of Step 5, an interactive calculator to specify economic optimum plant density (EOPD) for irrigated corn. Various screen shots of the calculator are illustrated. Standard US units of measure rather than SI are used as the target audience of this utility is the irrigated corn producer of Texas.

Conclusions

Our three EOPD models appear to accurately discriminate the effects of Texas climate on maize grain yields. For example, temperatures of North Texas are often ideal for maize production and produce high yields, whereas South Texas temperatures are often exceptionally high, especially during grain fill and produce low yields.

The general increase in average growing season temperatures from North, Central to South Texas corresponds with lower grain yield responses to increasing plant densities (Fig 1), overall lower grain yields, and lower economic returns (Fig 2).

The interactive EOPD calculator serves the producer by facilitating quick determinations of appropriate plant densities while accounting for changing seed costs and projected grain prices. The producer can manage risk by specifying their grain yield goal.

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