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ABSTRACT

Increased market demand and larger adoption of field pea (*Pisum sativum* L.) in semiarid west-central Nebraska has provided opportunities to replace summer fallow and diversify crop rotations. As a relatively new crop, its response to different seeding practices has not been evaluated in this eco-region. Field pea grain yield response to seeding depth (25, 50, and 75 mm), inoculation with *Rhizobium leguminosarum* *bv.* *viciae* (yes and no rhizobia inoculant), and seeding rates (35, 50, 65, 75, 90, 105, and 120 plants m⁻²) was investigated in 2015 and 2016 at five sites in Perkins County, NE. There were no differences in yield for field pea planted at depths of 25, 50, and 75 mm. Yield differences between inoculated and noninoculated field pea were not observed; however, a lack of nodules on noninoculated field pea plants suggests that carryover of rhizobia in soil with a history of field grown 2 to 3 yr previously was not sufficient to initiate nodulation. Seeding rates resulting in plant populations of 45 to 60 plants m⁻² provided the highest economic return; an economic penalty (~\$1.05 ha⁻¹) may occur for each additional plant per square meter attained over this plant population. Increasing the seeding rate, however, may help farmers manage risks of hail injury, enhance weed suppression, and increase harvest efficiency. Therefore, field pea grown in semiarid west-central Nebraska should be properly inoculated with rhizobia at every planting, seeded in good moisture at depths ranging from 25 to 75 mm, and have final plant population of at least 60 plants m⁻².

Core Ideas

- Field peas are a profitable crop in the semiarid Central Great Plains.
- Field peas in west-central Nebraska should be planted 25–75 mm deep.
- Field peas in west-central Nebraska need rhizobia inoculant at every planting.
- Field pea seeding rates may be reduced without lowering profits.
- Increase field pea seeding rates for weed suppression and harvest efficiency.

GRAIN-TYPE FIELD pea (*Pisum sativum* L.), also known as dry pea, is a cool-season (spring-planted) legume crop that may be grown as an alternative to summer fallow in semiarid regions of the Central Great Plains. Replacing fallow with field pea in traditional wheat–fallow or wheat–corn–fallow cropping systems may provide the following rotational benefits: (i) lower selection pressure for herbicide-resistant weeds through diversified crop rotation and inclusion of different herbicide modes of action (Norsworthy et al., 2012); (ii) increased diversity and abundance of beneficial insects and microorganisms (Altieri, 1999); (iii) reduced need for nitrogen (N) fertilizer, with an average addition of 10 to 24 kg N ha⁻¹ via fixation for the subsequent crop (Beckie and Brandt, 1997); (iv) increased soil organic carbon and soil microbial activity (Lupwayi et al., 2012); (v) increased precipitation storage efficiency and additional crop residue after harvest (Nielsen and Vigil, 2010); and (6) lower economic risk of farming and maintaining or even increasing profit levels (Miller et al., 2015). In addition, field pea is easy to implement because it requires minimal modification to rotations or farm equipment necessary for planting and harvest. However, field pea uses soil water and may potentially reduce the yield of the succeeding winter wheat crop, particularly in water-limited environments where off-season precipitation is not sufficient to replenish the soil profile (Nielsen et al., 2016). Nielsen et al. (2016) found an average reduction of 10% in wheat yield following a cover crop compared with wheat following fallow, with greater yield reduction in drier years. Unlike cover crops or fallow, field pea may be harvested and sold for grain, generating an economic return. Therefore, grain-type field pea may be a better replacement option to summer fallow than cover crops.

From 2011 to 2017, planted field pea acreage in the United States increased from 150,000 to 450,000 ha nationwide and from 4000 to approximately 23,000 ha in Nebraska alone (NASS, 2017). Increased adoption of field pea in the Central Great Plains may be attributed to the growing market demand, the seldom limited supply from major field pea growing regions (Canada, Northern Great Plains, and Pacific North West), and

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Abbreviations: a.i., active ingredient; AIC, Akaike's Information Criterion; EOPP, economically optimal plant population.

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the development of field pea processing facilities with locally available field pea delivery points (Minor and Bond, 2017). Markets for field pea are expected to grow due to (i) increased awareness of the health and nutrition benefits of pulse crops (including pea) in human consumption worldwide (United Nations General Assembly, 2016), (ii) its potential for use as a replacement in swine diets and cattle finishing diets (Jenkins et al., 2012; Njoka et al., 2007), (iii) growth in pet food industry spending and increased demand for pet food products marketed as “grain-free,” and (iv) increased demand for pea flour, pea protein concentrate, and pea fiber as the essential ingredients in value-added products marketed as gluten free, GMO free, and soy free (Cooper, 2015). Although adoption of field pea by farmers in the Central Great Plains (i.e., Nebraska, Kansas, Colorado, and Wyoming) is expected to continue increasing, the crop’s response to different agronomic practices, such as seeding rates, seeding depth, and inoculation with *Rhizobium leguminosarum* *bv. viciae* (rhizobia) bacteria, has, to our knowledge, not been evaluated in this eco-region.

Field pea is a large-seeded crop that generally requires deeper seeding than smaller-seeded cereals for good seed–soil contact (Table 1). To ensure proper germination and emergence, seeds should be placed at a soil depth with adequate moisture. Low topsoil moisture at planting is the main reason why deeper seeding is recommended for the drier and warmer climate of the Pacific Northwest (38 mm deep) as compared with Canada and the Northern Great Plains (25 mm deep) (Table 1). Although field pea can tolerate deeper seeding, seeding >76 mm deep may cause significant reduction in stand and up to 8.5% yield loss compared with shallower seeding (Johnston and Stevenson, 2001). Selection of the appropriate seeding depth to best fit each eco-region is therefore an important component in maximizing crop growth and yields.

Field pea is a legume capable of meeting a large portion of its N requirement through a symbiotic relationship with N-fixing rhizobia bacteria (Clayton et al., 2004). For this reason, application of rhizobia inoculant at planting is recommended across field pea–producing regions (Beck et al., 2015; Enders et al., 2016; McVay et al., 2016). The need to reintroduce rhizobia with each field pea growing season, however, depends on the ability of rhizobia to survive in the soil (Evans et al., 1993). Drew et al. (2012) surveyed Mediterranean soils and showed that the population of field pea rhizobia is likely to be under the optimal nodulation threshold (<100 rhizobia per gram of soil) when soil pH is <6.6, summers are hot and dry, and a plant host has been absent for more than 5 yr. To our knowledge, no studies have been conducted on the North American continent to describe the need for reintroduction of field pea rhizobia at sites that have a recent history of field pea production.

Optimal plant populations for field pea vary across the different eco-regions and under different management practices (Table 1). Target plant populations for field pea in the Northern Great Plains (Canadian provinces and North Dakota) range from 70 to 90 plants m⁻² and increase to 86 to 108 plants m⁻² for slightly warmer regions of the Pacific Northwest (Montana, Washington, and Idaho), South Dakota, Wisconsin, and Minnesota (Table 1). Higher plant populations for field pea are often recommended, especially in organic production, to increase the crop’s competitive ability against weeds (Baird et al.,

2009; Boerboom and Young, 1995; Corre-Hellou and Crozat, 2005; Grevsen, 2003). Boerboom and Young (1995) reported that increasing field pea population by 50% above the recommended stand of 88 plants m⁻² (132 plants m⁻²) caused up to 99% reduction in weed biomass under favorable conditions and 39% reduction under less favorable conditions. Increasing seeding rates, however, is not always economically justifiable due to seed cost. Nleya and Rickertsen (2011) reported seed cost to be a major input expense in commercial field pea production; hence, high seeding rates may adversely affect profitability. According to 2017 Nebraska Crop Budgets, planting certified field pea seed in Nebraska in 2016 at an average price of \$0.55 kg⁻¹ and a recommended seeding rate of 210 kg ha⁻¹ represented approximately 43% of total variable cost of production (Klein et al., 2017). More research is needed to develop optimal seeding rates in terms of maximizing economic net return and not exclusively maximizing yield (Nleya and Rickertsen, 2011). Therefore, the objectives of this study were to determine (i) the effects of seeding depth on field pea grain yield, (ii) the impact of rhizobia inoculant on field pea grain yield, and (iii) the economically optimal seeding rates for field pea in semiarid west central Nebraska.

MATERIALS AND METHODS

Description of Field Sites

Three separate field studies (seeding depth, rhizobia inoculant, and seeding rate) were conducted in 2015 and 2016 under established no-till systems at five different sites (East, West, North, South, and Central) in Perkins County, NE. The predominant soil type at the North, Central, and East sites was Rosebud loam (Fine-loamy, mixed, superactive, mesic Calcic Argiustolls) with 1 to 3% slopes. The predominant soil type at the South and West sites was Mace silt loam (Fine-silty, mixed, superactive, mesic Aridic Argiustolls) with 1 to 3% slopes (Table 2).

Seeding depth and rhizobia inoculant studies were conducted at the East and West sites in 2016. To evaluate the need for reintroduction of rhizobia inoculant at sites with varying history of field pea, we selected the East site, which had field pea grown in 2014 (2 yr before) and the West site, which had field pea grown in 2013 (3 yr before). Although the previous crop at both sites was proso millet (*Panicum miliaceum* L.), winter wheat (*Triticum aestivum* L.) was planted on 15 Sept. 2015 after the harvest of proso millet (28 Aug. 2015) at the East site in the fall of 2015. The following spring, the winter wheat was terminated with Roundup WeatherMAX (Monsanto, St. Louis, MO) application 1 d after planting the study crop (9 Apr. 2016). Late termination of winter wheat in 2016 at the East site caused a reduction in subsurface soil water (>100 mm deep) available to field pea; however, this was not the case at the West site, where field pea studies were planted in good subsurface soil moisture.

The seeding rate study was conducted at the North site in 2015 and at the Central and South sites in 2016 (Table 2). Winter wheat was the previous crop at the North and Central sites, and field corn (*Zea mays* L.) was the previous crop at the South site (Table 2). Top soil (0–100 mm) moisture conditions at planting were optimal (i.e., field capacity to 20% depletion) at all five sites. Soil samples were collected at each site at depths of 0 to 0.3, 0.3 to 0.6, and 0.6 to 0.9 m in the spring before planting (mid-March) and analyzed for pH, soluble salts, organic matter, available

Table 1. Seeding depth, seeding date, and seeding rate recommended for field pea in different regions of the North American continent.

Region	Seeding depth mm	Seeding date	Seeding rate plants m ⁻²	Source
Manitoba, CA	25–50	before 21 May	70–80	Manitoba Agriculture (2018)
Alberta, CA	25–50	before 15 May	75–90	Alberta Pulse Growers (2018)
Saskatchewan, CA	30–80	mid-Apr. to mid-May	75–85	Saskatchewan Pulse Growers (2016)
North Dakota	25–76	early Apr. to Mid-May	75–86	Enders et al. (2016)
Montana	25–76	late Mar. to early May	86–107	McVay et al. (2016)
South Dakota	38–65	mid-April	86	Beck et al. (2015)
Washington and Idaho	38–76	25 Mar.–10 May	89–108	Muehlbauer and Tullu (1997)
Wisconsin and Minnesota	25–65	mid-Mar. to mid-Apr.	95	Oelke et al. (1991)

Table 2. Description of field experiment sites including year, site, GPS coordinates, predominant soil type, and previous crop.

Study	Year	Site	Site-year	GPS coordinates	Predominant soil type	Previous crop
Seeding depth and Rhizobia inoculant	2016	East	East-16	40°47'29" N, 101°57'14" W	Rosebud loams, 1–3% slopes	proso millet †
	2016	West	West-16	40°47'17" N, 101°58'20" W	Mace silt loam, 1–3% slopes	proso millet
Seeding rate	2015	North	North-15	40°48'25" N, 101°57'41" W	Mace silt loam, 1–3% slopes	winter wheat
	2016	Central	Central-16	40°47'17" N, 101°57'24" W	Rosebud loams, 1–3% slopes	winter wheat
	2016	South	South-16	40°44'02" N, 101°58'16" W	Mace silt loam, 1–3% slopes	field corn

† Winter wheat was planted on 15 Sept. 2015 after the harvest of proso millet (28 Aug. 2015) at the East site in the fall of 2015, and the crop was terminated the following spring (9 Apr. 2016) using Roundup WeatherMAX applied 1 d after planting the studies.

nitrate-N (NO₃-N), phosphorus (P), and potassium (K). Soil nutrient levels (excluding NO₃-N) were above sufficiency levels, and soil pH in the top 0.3 m was in a desirable range (6.2–7.0) at all sites (Shaver et al., 2014). Weather conditions for the 2015 and 2016 growing seasons, as well as the 30-yr averages for the region, recorded at Venango, NE, are summarized in Table 3.

Experimental Design and Data Collection

Seeding Depth Study

The seeding depth study was conducted in 2016 at the East and West sites as a randomized complete block design with four replications. Treatments consisted of seeding depths of 25, 50, and 75 mm. Experimental plots were 1.5 m wide × 6 m long. Field pea seed (DS Admiral; Pulse USA, Bismarck, ND) was treated with XiteBio PulseRhizo liquid rhizobia inoculant (XiteBio Technologies Inc., Winnipeg, MB, Canada) at 75 mL kg⁻¹ and planted on 8 Apr. 2016 using a 1.5-m-wide drill planter (SRES Seed Research Equipment Solutions, South Hutchinson, KS) with 25-cm row spacing. The drill was calibrated to deliver 186 kg seeds ha⁻¹, for a target population of 75 plants m⁻². One day after planting (9 Apr. 2016), Sharpen (BASF Corporation, Research Triangle Park, NC) at 140 g active ingredient (a.i.) ha⁻¹, Spartan Charge (FMC, Philadelphia, PA) at 350 g a.i. ha⁻¹, and Roundup WeatherMAX at 2242 g a.i. ha⁻¹ were applied for burndown and pre-emergence weed control at both sites.

Field pea population data (plants m⁻²) were collected on 11 May 2016 after crop emergence ceased (V4 growth stage) by counting the number of plants in the middle two rows of the entire plot length (6 m). When field pea plants reached the V6 to V8 growth stage (seven-leaf), five plants from the edge of the plot were dug out with the shovel, and their roots were gently washed in a bucket of water to determine the presence or absence of visual nodulation. The N-fixation was evaluated by cutting the

nodules in half and confirming light-pick coloration of the plant tissue. At harvest (16 July 2016), a 1.2 m⁻² area in the center four rows of each plot was hand clipped, grain was threshed by hand, and total grain weight was recorded. The grain moisture content was recorded using a grain moisture meter (Farmex MT-PRO; FarmComp, Tuusula, Finland), and final grain yield (kg ha⁻¹) was adjusted to 12% moisture content for treatment comparison.

Rhizobia Inoculant Study

The rhizobia inoculant study was conducted in 2016 at the East and West sites as a randomized complete block design with four replications and two treatments: (i) field pea seed inoculated with rhizobia (inoculated) and (ii) noninoculated field pea seed (noninoculated). The experimental plots were 1.5 m wide × 6 m long. Field pea cultivar DS Admiral (Pulse USA) was planted at uniform seeding depth of 50 mm on 8 Apr. 2016 using a 1.5-m-wide SRES drill planter with 25-cm row spacing (SRES Seed Research Equipment Solutions). The noninoculated plots were planted first to avoid contamination of rhizobia inoculant on the seed. Field pea seed was then treated with liquid rhizobia inoculant (PulseRhizo; XiteBio Technologies Inc.) at 75 mL kg⁻¹ to plant inoculated treatment. Seeding rate, herbicide program, and data collection procedures (including stand counts, nodulation inspection, and grain harvest) for this study were identical to the aforementioned seeding depth study.

Seeding Rate Study

The seeding rate study was conducted on a large scale using commercial farm machinery for all cultural practices. The experiment was set up as a randomized complete block design with seven treatments (seeding rates) replicated four times. The choice of seeding rates was based on the currently recommended plant population of 75 plants m⁻², with three populations under the final recommended stand (35, 50, and 65 plants m⁻²),

Table 3. The 2015, 2016, and 30-yr average minimum, maximum, and mean monthly temperatures and sums of monthly rainfall during the field pea-growing season (March–July) for five research sites at Perkins County, NE, recorded at a weather station at Venango, Nebraska.

Month	2015				2016				30-yr average			
	Temperature			Rainfall	Temperature			Rainfall	Temperature			Rainfall
	Min.	Max.	Mean		Min.	Max.	Mean		Min.	Max.	Mean	
°C			mm	°C			mm	°C			mm	
Mar.	–2	18	8	4	–3	15	6	21	–4	11	4	28
Apr.	2	18	10	76	2	16	9	137	1	17	9	52
May	7	19	13	188	6	21	14	93	7	22	15	79
June	14	29	22	70	14	32	23	37	13	28	20	82
July	15	32	24	109	16	31	23	71	16	32	24	79

the recommended rate (75 plants m⁻²), and three over (90, 105, and 120 plants m⁻²), for a total of seven treatments. Drills were calibrated for seeding rate (kg ha⁻¹) by dividing the targeted plant population (plants ha⁻¹) by seed weight (seeds kg⁻¹) and adjusting for percent germination rate for a particular field pea cultivar. The study seeds were planted in strips, and the dimensions were the width of the drill available at each location (which varied from 12 to 14 m wide) by 100 m long.

At the North site in 2015 (North-15), ‘DS Admiral’ field pea (germination 0.91) was planted using a 12-m-wide Morris 7240 Air Tank drill (Morris Industries LTD, Saskatoon, SK, Canada) with 25-cm row spacing on 1 May 2015. The same drill was used for the Central-16 site-year to plant ‘Early Star’ (Meridian Seeds LLC., Casselton, ND) field pea (germination 0.90) on 7 Apr. 2016. At the South-16 site-year, a 14-m-wide CrustBuster All Plant Drill 4745 (CrustBuster/Speed King Inc., Dodge City, KS) with 25-cm row spacing was used to plant ‘Salamanca’ (Great Northern Ag, Plaza, ND) field pea on 7 Apr. 2016. Seeds were planted at 50 mm deep, and a combination of PulseRhizo liquid (XiteBio Technologies Inc.) at 75 mL kg⁻¹ and TagTeam LCO granular (Monsanto) at 3.7 kg ha⁻¹ rhizobia inoculants was applied to seed at planting time at all site-years. The herbicide program at North-15 included a single burndown application of Roundup WeatherMAX at 2242 g a.i. ha⁻¹ on 2 May 2015 (1 d after planting). The herbicide program at the Central-16 and South-16 sites was applied on 30 Mar. 2016 and 3 Mar. 2016, respectively, and included Spartan Charge (FMC) at 350 g a.i. ha⁻¹ tank-mixed with Roundup WeatherMAX at 2242 g a.i. ha⁻¹ and applied prior to crop emergence.

Plant population data (plant m⁻²) were collected at V3 to V5 growth stage by conduction of four counts per strip. Stand counts were taken from a 1.5-m² quadrat randomly placed within the strip area on 1 June 2015, 18 May 2016, and 11 May 2016 for North-15, Central-16, and South-16, respectively. Grain yield data were collected by harvesting the middle 10 m of the 100-m-long strip using a 10-m-wide Axial-Flow Case 6088 combine (Case IH Agriculture, Racine, WI). After each strip was harvested, a grain cart with a built-in scale was used to record grain weight, and a subsample of grain was taken from the combine to record grain moisture content. Final grain yield was adjusted to 12% moisture for each plot. The grain was harvested on 28 July 2015, 22 July 2016, and 23 July 2016 at North-15, Central-16, and South-16, respectively.

Statistical Analysis

Seeding Depth and Rhizobia Inoculant

Grain yield data from seeding depth and rhizobia inoculant studies were subjected to ANOVA using the PROC GLIMMIX procedure with SAS software version 9.1 to test for the significance ($P < 0.05$) of site, study treatment, and their interactions (SAS Institute, 2005). Experimental block was treated as a random effect in the model; site and treatment level were considered fixed effects. The PROC UNIVARIATE procedure and Shapiro–Wilk normality test were used to assure that data were normally distributed. Means for the significant treatment effects were compared using Fisher’s protected least significant difference procedure at $P < 0.05$.

Seeding Rate

AIC Model Selection. A set of regression models commonly used to characterize grain yield in response to plant populations was selected, and each model was fit to the pooled data across all three sites (North-15, Central-16, and South-16). Candidate regression models were linear (McDonald et al., 2007), quadratic (Lawson 1982), Michaelis–Menten (Baird et al., 2009), and asymptotic (Gooding et al., 2002):

1. Linear (first-order polynomial):

$$Y = a + bX \quad [1]$$

2. Quadratic (second-order polynomial):

$$Y = a + bX + cX^2 \quad [2]$$

3. Michaelis–Menten (MM):

$$Y = \frac{\alpha * X}{\kappa + X} \quad [3]$$

4. Two-parameter Asymptotic Regression (AR2):

$$Y = \alpha[1 - \exp(-X/\kappa)] \quad [4]$$

where Y is grain yield (kg ha⁻¹), X is plant population (plants ha⁻¹), a is the intercept, b is the linear term, c is the quadratic term, α is the asymptote (maximum grain yield), and κ is the shape parameter. The adequacy of a model among the pool of candidates was accessed using the information-theoretic model comparison approach, also known as Akaike’s Information Criterion (AIC) (Burnham and Anderson, 2002). In

Table 4. Field pea grain yield as affected by seeding depth and rhizobia inoculant.

Study treatments	Site-year		Study treatments	Site-year	
	East-16	West-16		East-16	West-16
Seeding depth (mm)	yield (kg ha ⁻¹)		Rhizobia inoculant	yield (kg ha ⁻¹)	
25	692	1478	Noninoculated	677	1371
50	876	1552	Inoculated	876	1552
75	805	1662	Average	776 b	1461 a
Average	791 b†	1564 a			
	ANOVA			ANOVA	
Source of variation	df	Significance	Source of variation	df	Significance
Site-year (SY)	1	***	SY	1	***
Seeding depth (SD)	2	ns‡	Inoculant (I)	1	ns
SY × SD	2	ns	SY × I	1	ns
CV%		25	CV%		25

*** Significant at the 0.001 probability level.

† Within a row, means followed by the same letter are not significantly different according to LSD (0.05).

‡ Nonsignificant.

information theory, AIC represents the Kullback–Leibler distance between the model and the “truth” and is calculated as:

$$AIC = -2 \ln(L) + 2k \quad [5]$$

where k is the number of estimated parameters in the model, and $\ln(L)$ is the log-likelihood function for the model. Therefore, the preferred model among the pool of candidates is the one with the lowest AIC value. To rank the models, AIC difference ($\Delta_i AIC$) was calculated as the difference between the AIC of the best model (AIC_{\min}) and the AIC of i^{th} model (AIC_i):

$$\Delta_i AIC = AIC_i - AIC_{\min} \quad [6]$$

The $\Delta_i AIC$ values were then rescaled to Akaike weights (w_i) using Eq. [7] (Burnham and Anderson, 2002). The w_i values sum to 1 and indicate the probability of model i being the best model among the pool of candidates:

$$w_i = \frac{\exp(-0.5x \Delta AIC_i)}{\sum_{k=1}^k \exp(-0.5x - \Delta AIC_k)} \quad [7]$$

Stepwise Regression Using Backward Elimination. Stepwise regression using backward elimination was used for the model selection procedure as described by Wang et al. (2016) to select the most parsimonious AR2 model for the dataset (i.e., the model that accomplishes a desired level of explanation with as few parameters as possible) from the three site-years (North-15, Central-16, and South-16). The procedure starts with fitting a “full” least squares model containing all parameters (e.g., α and κ fit to each site) and then removes parameters that are not helping improve the model (“reduced model”) one at a time until parameter removal does not result in model improvement (Wang et al., 2016). The criteria for exclusion of the predictor variable is assessed by F-test (variance ratio) at the 0.05 α level (Wang et al., 2016). The procedure aims to prevent the overfitting of the model that occurs when the regression model has a tendency to capture the individual observations rather than an overall pattern within the dataset (Wang et al., 2016). As a result, the most parsimonious model is used to describe the data (i.e., the

model that accomplishes a desired level of explanation with as few parameters as possible). The statistical analyses and graphical representations for the seeding rate study were performed using R (R Core Team, 2014) and R Studio (RStudio Team, 2015). **Economically Optimal Plant Population.** The economically optimal plant population (EOPP) was performed to determine the field pea planting population (plants m⁻²) that maximizes the partial net return (\$ ha⁻¹) made on the investment, in this case purchase of seed (Nleya and Rickertsen, 2011). The partial net return (NR, \$ ha⁻¹) was calculated as (Nleya and Rickertsen, 2011):

$$NR = Y \times Pr - C \times Po \quad [8]$$

where Y is field pea grain yield (kg ha⁻¹), Pr is field pea grain price (\$ kg⁻¹), C is the average cost of field pea seed, and Po is the plant population (plants m⁻²). Field pea grain price (Pr) was set to 0.15, 0.25, or 0.35 \$ kg⁻¹ to represent the wide range of market prices for field pea in Nebraska from 2014 to 2017. The new dataset was generated to obtain field pea grain yield (Y) for the range of plant populations (Po) using the best ranked regression model according to the aforementioned AIC model selection procedure. Acreage cost of field pea seed (C) was calculated assuming 90% germination rate (0.90), seed weight of 4631 seeds kg⁻¹, and price of certified seed treated with rhizobia inoculant of \$0.55 kg⁻¹ (Klein et al., 2017). The EOPP was then determined as the point on the curve that provided maximum partial net return.

The statistical analyses and graphical representations for the seeding rate study were performed using R (R Core Team, 2014) and R Studio (RStudio Team, 2015).

RESULTS AND DISCUSSION

Seeding Depth Study

Seeding depth had no impact on field pea grain yield (Table 4). Field pea grain yield at East-16 (791 kg ha⁻¹) was lower than at West-16 (1564 kg ha⁻¹) (Table 4). This corroborates the results of other studies that reported no difference in field pea grain yield for seeding depths ranging from 25 to 76

Table 5. Number of parameters (k), corrected Akaike's Information Criterion (AICc), rescaled AICc (Δ_i AICc), and Akaike's weights (w_i) of predictive models for field pea grain yield response to plant population.

Models	k	AICc	Δ_i AICc	w_i
Two-parameter asymptotic regression (AR2)	2	1198.86	0.00	0.35
Michaelis–Menten (MM)	2	1198.99	0.14	0.33
Linear (first-order polynomial)	2	1199.15	0.29	0.31
Quadratic (second-order polynomial)	3	1206.31	7.45	0.01

mm when sufficient top soil moisture was present at planting (Enders et al., 2016; Johnston and Stevenson, 2001; Tawaha and Turk, 2004). According to Johnston and Stevenson (2001), seeding deeper than 76 mm in optimal top soil moisture conditions may cause a reduction in crop stand and up to 8.5% grain yield reduction compared with shallower seeding depths. Increasing seeding depths in semiarid environments, however, may be required to ensure adequate moisture for germination and seedling emergence (Tawaha and Turk, 2004). Enders et al. (2016) recommend that field pea should be seeded at least 13 mm into moisture and never seeded onto the interface where soil moisture meets dry soil.

Rhizobia Inoculant Study

Rhizobia inoculant had no impact on field pea grain yield ($P = 0.2033$) (Table 4). Grain yield differences were observed between the two site-years ($P = 0.0004$), with field pea yielding on average 776 kg ha⁻¹ at East-16 and 1461 kg ha⁻¹ at West-16 (Table 4). Nodulation inspection at the V6 to V8 growth stage showed an absence of nodules in plots where rhizobia inoculant was not applied; therefore, carryover of rhizobia in soil where field pea was grown 2 yr (East-16) and/or 3 yr (West-16) before was not sufficient to initiate field pea nodulation. Before planting, available NO₃-N in the top 0.9 m of soil was 10 kg ha⁻¹ at East-16 and 36 kg ha⁻¹ at West-16, suggesting that available NO₃-N along with N released from mineralization of organic matter was likely sufficient to meet the N demand of noninoculated field pea in our study. The application of rhizobia inoculant at planting is highly recommended to ensure a large and effective colonization and development of root nodules and fixation of N for the crop (Beck et al., 2015; Enders et al., 2016; McVay et al., 2016). Although rhizobia inoculation may not be necessary for certain fields that have a history of field pea, applying inoculant to ensure good nodulation remains a standard agronomic practice due to the complexity of factors influencing the survival of rhizobia populations and their symbiotic performance in various soil types and climatic conditions (Drew et al., 2012). Further research is required to evaluate interseasonal variability in soil and climatic conditions on the need for rhizobia inoculant in southwestern Nebraska.

Seeding Rate Study

Based on the AIC model selection procedure, AR2 (Eq. [4]) was the model with the highest probability (w_i , Akaike's weight) and was the most accurate predictor of field pea grain yield response to plant population among the tested models (Table 5). According to the backward selection algorithm, the most parsimonious AR2 predictive model was the one with a common κ parameter (shape parameter) for all sites and an α parameter (maximum yield) estimated for each site-year separately. Parameter estimates

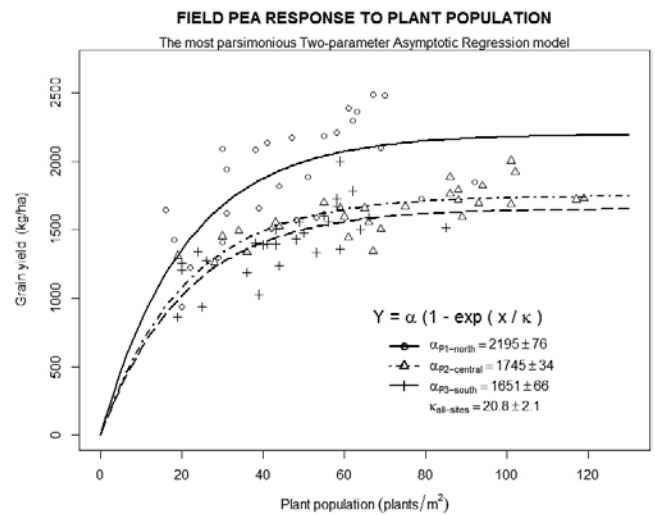


Fig. 1. Parameter estimates (α = maximum yield, κ = shape parameter) and their standard errors (\pm SE) for the most parsimonious two-parameter asymptotic regression model used in predicting field pea grain yield response to plant population in semiarid environment of west-central Nebraska.

and their associated standard errors for the AR2 predictive model used for our three site-years are shown in Fig. 1.

The overall response of field pea grain yield to plant population was linear at lower densities (<40 plants m⁻²) and began to plateau at approximately 40 plants m⁻², reaching its maximum at approximately 70 plants m⁻² (Fig. 1). Maximum field pea grain yield was higher at North-15 (2195 kg ha⁻¹) compared with Central-16 (1745 kg ha⁻¹) and South-16 (1651 kg ha⁻¹). Furthermore, field pea at North-15 was more responsive to increasing populations than at the other two site-years. For instance, field pea grain yield increased by almost 1000 kg ha⁻¹ (from 1200 to 2195 kg ha⁻¹), going from 20 to 75 plants m⁻² at North-15, whereas yield increase for the same plant population range at Central-16 and South-16 was 800 and 700 kg ha⁻¹, respectively. Although yield response at plant populations >70 plants m⁻² was seldom observed, our data from the North-15 site-year indicates that field pea may respond to higher plant populations under favorable environmental conditions. Higher yield goals for field pea might be obtained under irrigation or in years when lower temperature and higher precipitation occur during the reproductive growth stages (Bueckert et al., 2015; Guilioni et al., 2003).

Johnston et al. (2002) reported results similar to our finding of no increase in field pea grain yield at seeding rates >50 plants m⁻². Most reports, however, showed increases in field pea grain yield at plant populations as high as 90 plants m⁻² (Tawaha and Turk, 2004), 146 plants m⁻² (Baird et al., 2009), 140 to 195 plants m⁻² (Lawson, 1982), and 200 plants m⁻² (Mc Donald et al., 2007). Boerboom and Young (1995) suggested that such variable responses of field pea in seeding rate studies are likely influenced by a combination of biotic (e.g., disease) and abiotic factors (e.g., heat stress and/or water deficit). Others reported the lack of yield response at higher seeding rates because of the compensatory nature of field pea to branch and produce higher grain yield per plant at low seeding rates (Boerboom and Young, 1995; Johnston et al., 2002; Nleya and Rickertsen 2011; Tawaha and Turk, 2004). For example, Tawaha and Turk (2004) reported that decreasing seeding rates from 90 to 30 seeds m⁻² decreased

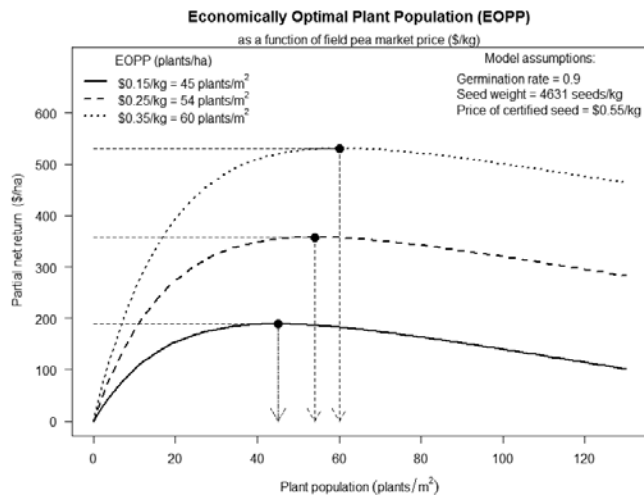


Fig. 2. Economically optimal plant populations for field pea grain prices of \$0.15, 0.25, and 0.35 kg⁻¹ assuming a germination rate of 0.9, seed weight of 4631 seeds kg⁻¹, and price of certified field pea seed of \$0.55 kg⁻¹.

field pea grain yield by 50%, whereas 100 seed weight, seed weight per plant, number of seeds per pod, and number of pods per plant were increased by 23, 32, 34, and 40%, respectively. Additional research is needed to further understand the response of field pea yield and yield components to seeding rates in semi-arid environments of the Central Great Plains.

Economically Optimal Plant Population

Seeding rate affects canopy development, crop ability to suppress weeds, grain yield, and, ultimately, profitability; therefore, these factors must be taken into consideration when selecting EOPP. Our results suggest that maximum partial net return for field pea grown in a weed-free environment was obtained at 45, 54, and 60 plants m⁻² to for market grain prices of \$0.15, 0.25, and 0.35 kg⁻¹, respectively (assuming 90% germination and 4631 seeds kg⁻¹; plant population of 45, 54, and 60 plants m⁻² corresponds to seeding rates of 87, 104, and 116 kg ha⁻¹, respectively) (Fig. 2). A penalty of approximately \$1.05 ha⁻¹ occurred when adding an additional plant m⁻² over the EOPP. In terms of seeding rate, a penalty of \$0.41 ha⁻¹ occurred for each additional kg ha⁻¹ of seed planted over the EOPP. Other researchers have reported a point of maximum economic return to be similar to ours when field pea is grown under relatively weed-free conditions (Johnston et al., 2002; Nleya and Rickertsen, 2011). Johnston et al. (2002) found that economic returns from seeding rates above 50 plants m⁻² may not warrant the extra seed cost. Nleya and Rickertsen (2011) reported that best partial net economic returns may vary from year to year, but generally lower returns were found at seeding rates >77 seeds m⁻². When field pea is grown under conditions where herbicide use is limited and weed pressure is high, higher plant populations increase crop competition against weeds, and increased seeding rates may be economically justified (Baird et al., 2009). Baird et al. (2009) found that increasing the seeding rate decreased weed biomass up to 68%. Therefore, the maximum economic return in their study was observed at a seeding rate of 200 seeds m⁻² and at an actual plant population of 120 plants m⁻², which is much higher than the EOPP found in this study. They also reported that higher seeding

rates may be constrained by the increased cost of additional seed (Baird et al., 2009). Seeding rate studies conducted throughout North America recommend plant populations of at least 75 plants m⁻² as a means of managing risk of hail injury, weed suppression and accelerated dry down, and more efficient direct harvest (Beck et al., 2015; Enders et al., 2016; McVay et al., 2016).

CONCLUSIONS

We observed no difference in field pea grain yield when seed was planted at depths of 25 to 75 mm and in good soil moisture. Field pea seed should be planted 25 to 75 mm deep, when moisture is present, with good seed–soil contact. Although yield differences between inoculated and noninoculated field pea were not observed, noninoculated field pea did not produce nodules and had to rely on residual soil N rather than on biological fixation. Therefore, the use of inoculant at planting is recommended until further research is conducted to evaluate field pea N demand and carryover of rhizobia in soils of the semiarid Central Great Plains. Current recommendations for field pea seeding rates target plant populations of 70 to 108 plants m⁻² (Table 1). Our results demonstrate the potential for reduced field pea seeding rates without lowering profits. Seeding rates targeting plant populations of 45 to 60 plants m⁻² provided the highest economic return for field pea grain prices of \$0.15 to 0.35 kg⁻¹; a penalty of \$1.05 ha⁻¹ may occur for each additional plant m⁻² attained over the EOPP. Along with other practices, including tillage, residue management, variety selection, and planting date, proper seeding practices, such as seed depth, inoculant, and seeding rate, are essential for rapid germination, canopy development, achieving high grain yield, and ultimately raising a profitable field pea crop.

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