Made available through Montana State University's ScholarWorks

# Planting date and seeding rate of field pea in the semi-arid high plains of Nebraska

Samual T. Koeshall, Amanda C. Easterly, Rodrigo Werle, Strahinja V. Stepanovic, Cody F. Creech

This is the peer reviewed version of the following article: [Planting date and seeding rate of field pea in the semi‐arid high plains of Nebraska. Agronomy Journal (2020)], which has been published in final form at https://doi.org/10.1002/agj2.20535. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions: https://authorservices.wiley.com/author-resources/Journal-Authors/licensing/self-archiving.html#3.

Accepted Article

TITLE:

# Planting Date and Seeding Rate of Field Pea in the Semi-Arid High Plains of Nebraska

**AUTHORS:**

**Samuel T. Koeshall[1], Amanda C. Easterly[2], Rodrigo Werle[3], Strahinja V. Stepanovic[4], & Cody F. Creech[5*]**

[1]Montana State University, Department of Land Resources and Environmental Sciences, 334 Leon Johnson Hall, Bozeman, MT 59715

[2]University of Nebraska – Lincoln, Department of Agronomy and Horticulture, High Plains Agricultural Laboratory, 3257 Road 109, Sidney, NE 69162

[3]University of Wisconsin – Madison, Department of Agronomy, 1575 Linden Drive., Madison, WI 53706

[4]University of Nebraska – Lincoln, Henry J. Stumpf International Wheat Center, 76025 Rd 329, Grant, NE 69140

[5]University of Nebraska – Lincoln, Department of Agronomy and Horticulture, Panhandle Research and Extension Center, 4502 Ave 1, Scottsbluff, NE 69361-4939

[*]Corresponding Author (ccreech2@unl.edu)

## ABSTRACT

Results from initial experiments in western Nebraska suggest that opportunity exists to decrease seeding rates of pea (*Pisum sativum* L.) to optimize yield while maintaining partial net return. Refined planting recommendations, especially planting time, are still largely unknown for western Nebraska. This experiment evaluated the effects of seeding rates and

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/agj2.20535.

This article is protected by copyright. All rights reserved.

Accepted Article

planting dates of pea on emergence, grain yield, and grain yield components. Two locations in Nebraska were evaluated in 2018 and 2019. Treatments consisted of three planting dates and five seeding rates arranged as a split-plot design. Emergence was measured in each plot until emergence stabilized. Whole plant biomass, pods plant$^{-1}$, seeds plant$^{-1}$, and harvest index were recorded at harvest. Planting later resulted in increased plant density and decreased time to 50 and 90% emergence. Planting date also changed the economically optimal plant population. At Sidney in 2018, optimal plant population changed from 96 plants m$^{-2}$ (Early) and 115 plants m$^{-2}$ (Late) to 82 plants m$^{-2}$ (Middle). Partial net return was increased by \$26.74 ha$^{-1}$ and \$65.43 ha$^{-1}$ with the middle planting date over the early and late planting dates. Across three site-years, the economically optimal plant population only varied by 4 plants m$^{-2}$ between the three planting dates. Later planting improves percent emergence without reducing yield. Seeding rates that have been adjusted for expected germination should target a population between 70 and 109 plants m$^{-2}$ to optimize partial net return. Final plant population influences grain yield more than planting date, although both affect yield response.

## ABBREVIATIONS

1. EOPP: Economically optimal plant population
2. GDD: Growing degree day
3. PLS: Pure live seed

## CORE IDEAS

1. Planting date and seeding rate influenced pea emergence.
2. Planting date, site-year, and year changed the time to 50 and 90% emergence of pea.
3. Target seeding rates should be based on the economically optimal plant population.

This article is protected by copyright. All rights reserved.

Accepted Article

4. Grain yield of field pea is optimized by planting field pea in mid to late March in western Nebraska.
5. Economically optimal plant populations between 70 – 109 plants $m^{-2}$ optimize grain yield.

## INTRODUCTION

Field pea (*Pisum sativum* L.) has been shown to promote positive ecological responses in cropping systems such as improved soil microbiome health, soil fertility, landscape precipitation use efficiency while mitigating soil erosion, reducing the use of chemical summer fallow, and improving subsequent crop yields (Miller *et al*., 2002, 2006b; Adderley *et al*., 2006). Additionally, farm profitability is usually improved when pea is incorporated into wheat-based cropping systems while improving annualized yield and minimizing farm-scale yield variability (Dhuyvetter *et al*., 1996; Anderson *et al*., 1999; Tanaka *et al*., 2002; Miller *et al*., 2003). Thus, pea has become an optimal legume in water-limited environments (Joshi and Rao, 2017). Agronomic benefits of pea have contributed to increased adoption of the crop across the Pacific Northwest and Great Plains with pea totaling 270,000 hectares in the United States in 2018 (USA Dry Pea & Lentil Council, 2018).

Achieving optimal yield potential and profitability in pea begins with proper planting practices, particularly when it comes to seeding rates and planting timing (Johnston *et al*., 2002; Gan *et al*., 2003; Miller *et al*., 2006a; Stepanovic *et al*., 2018). Optimal planting date of pea is limited by spring soil moisture and soil temperature at time of seeding. It can be delayed if the soil is frozen (Oelke *et al*., 1991; Meyer and Badaruddin, 2001; Schatz and Endres, 2009; Pavek, 2012). In addition to planting date, seeding rate can influence yield components, competition with weed species, foliar pathogen development, and microclimate

This article is protected by copyright. All rights reserved.

Accepted Article

factors within the canopy (Gan *et al*., 2003; Hwang *et al*., 2006; Nleya and Rickertsen, 2011; Fernandez *et al*., 2012; Stepanovic *et al*., 2018).

Field pea is able to tolerate low air temperatures after emergence and germinate in relatively cold, wet conditions with a growing degree day (GDD) base of 0° C (Welbaum *et al*., 1997; Meyer and Badaruddin, 2001; Schatz and Endres, 2009). Most pea types are able to withstand harsh climate conditions as young seedlings down to 10° C or as low as -30° C if covered by a layer of snow without significant plant injury (Meyer and Badaruddin, 2001; Pavek, 2012). However, prolonged exposure to harsh freeze events will reduce plant vigor and may decrease yield potential (Meyer and Badaruddin, 2001; Miller *et al*., 2006a). Conversely, prolonged exposure of pea to high air temperatures during flower development will reduce pods plant$^{-1}$ and grain yield (Tawaha and Turk, 2004; Miller *et al*., 2006a).

Although spring frost can damage pea seedlings, cultivars of yellow pea have been bred to tolerate cold temperatures and earlier planting dates (Meyer & Badaruddin, 2001; Oelke *et al.*, 1991; Pavek & NRCS Pullman Plant Materials Center, 2012; Schatz & Endres, 2009; Fernandez *et al.*, 2012; Johnston *et al.*, 2002; Miller *et al.*, 2006a). Earlier planting of pea may decrease emergence if sudden cold weather conditions are present after planting (Welbaum *et al*., 1997; Meyer and Badaruddin, 2001; Schatz and Endres, 2009; Pavek, 2012). However, other research found that planting date did not affect final planting density of pea but delayed planting of pea reduced grain yield and plant height (Miller *et al*., 2006a). Tawaha and Turk (2004) showed similar results in a planting date study of pea in the Mediterranean region as Miller *et al.* (2006a) found in a Northern Great Plains study. Both studies observed that delayed planting, due to warmer temperatures and therefore a shorter growing season, negatively influenced yield, yield components, and time to maturity.

In some crops such as soybean (*Glycine max* L.), the ability of the plant to "flex" and adjust to variations in planting density can allow farmers to maintain current yields while

This article is protected by copyright. All rights reserved.

Accepted Article

decreasing seeding rates, which results in achieving the ideal EOPP and reducing overall seed costs (De Bruin and Pedersen, 2008). However, for pulse crops such as yellow pea, increasing the seeding rate excessively can lead to decreased pod count per plant and seed yield per plant (French, 1990; Tawaha and Turk, 2004; Nleya and Rickertsen, 2011). The optimal seeding rate of field pea changes across eco-regions as previous studies have shown (Tawaha and Turk, 2004; Nleya and Rickertsen, 2011; Stepanovic *et al*., 2018). Tawaha and Turk (2004) suggested a seeding rate of 90 plants $m^{-2}$ for the semi-arid Mediterranean whereas Stepanovic *et al.* (2018) noted that optimal yield and profitability of yellow pea occurred when seeding rates were between 45 – 60 plants $m^{-2}$ for west-central and south-west Nebraska in the Central Great Plains. Due to the growing interest in yellow field pea across western Nebraska, discovering the optimal seeding rate of pea across the panhandle region of western Nebraska would improve yield and optimize net returns to the farm operation, similar to seeding rate studies from other site-specific regions (Tawaha and Turk, 2004; Nleya and Rickertsen, 2011; Stepanovic *et al*., 2018).

Planting practices determine a majority of the crop yield potential and partial net return realized by the farm unit. Developing regionally specific planting recommendations for pea can enhance crop harvestability, grain yield, and overall profitability while reducing prolonged exposure to harsh environmental conditions during flowering and seed set (Johnston *et al*., 2002; Gan *et al*., 2003; Tawaha and Turk, 2004; Baird *et al*., 2009; Nleya and Rickertsen, 2011). Overall, the benefits and disadvantages of early or late planting dates and high or low seeding rates requires a careful balance of these establishment factors that influence yield potential and maximum partial net return. However, the ideal combination of certain planting dates and seeding rates are largely unknown for western Nebraska. The objective of this experiment was to evaluate the effects of seeding rate and planting date on pea grain yield and physiology. The results from this experiment provides planting date and

This article is protected by copyright. All rights reserved.

Accepted Article

seeding rate recommendations for yellow pea growers across the panhandle region of western Nebraska, complementing the yellow pea seeding rate recommendations for west-central and south-central Nebraska growers formulated by Stepanovic *et al*. (2018).

## MATERIALS AND METHODS

Experiments were conducted near Sidney and Hemingford, NE during 2018 and 2019. All sites were managed under a no-till system. The predominant soil series at Sidney was an Alliance Aridic Argiustoll (2018) and Sidney Torriothentic Haplustoll (2019) whereas at Hemingford the predominant soil series was an Alliance Aridic Argiustoll (2018) and Rosebud Calcidic Argiustoll (2019) during the two-year experiment. The Köppen-Geiger climate classification for both Sidney and Hemingford, NE is BSk (Beck *et al*., 2018). Growing season precipitation at Sidney was 246 and 285 mm whereas Hemingford precipitation amounted to 367 and 431 in 2018 and 2019, respectively. The experimental design was a randomized complete block in a split-plot arrangement with six replications. Whole plot unit was planting date and split-plot unit was seeding rate. Target planting dates were the first week of March, third week of March, and first week of April. Actual planting dates are listed in Table 1 and did not always match the target dates due to field conditions that altered planting timing. There were five seeding rates used within each planting date as follows: 32 PLS $m^{-2}$, 54 PLS $m^{-2}$, 77 PLS $m^{-2}$, 99 PLS $m^{-2}$, and 121 PLS $m^{-2}$. Each plot was 9.9 meters long and 1.5 meters wide. Before planting, weeds were controlled using Roundup PowerMax® (a.i: glyphosate, N-(phosphonomethyl)glycine) at a rate of 1542 g ai $ha^{-1}$ and Spartan Charge® (a.i: carfentrazone-ethyl and sulfentrazone) at a rate of 240 g ai $ha^{-1}$ as a pre-emergent herbicide.

Nette 2010 yellow field pea (PULSE USA, Bismarck, ND) was used both years at both research sites. Pea seeds were inoculated with Verdesian N-DURE© powder (*Rhizobium leguminosarum biovar viceae* 2 x 108 CFU/g) (Verdesian Life Sciences, Cary, NC) at a rate

This article is protected by copyright. All rights reserved.

Accepted Article

of 1.86 kg per 680 kg of seed and treated the day of planting. Field peas in experimental plots were seeded 5 cm deep in rows spaced 19 cm apart using an 8-row SRES research plot drill (Seed Research Equipment Solutions, South Hutchinson, KS). The seeding rate treatment for each plot was adjusted for germination based on the pure live seed count $kg^{-1}$. Pure live seed (PLS) count per kilogram of seed was calculated by the Nebraska Crop Improvement Association laboratory in Lincoln, Nebraska.

An area of 0.762 $m^{-2}$ was marked within each plot that encompassed four center rows at one meter in length to measure emergence over time at all locations. Emergence was recorded approximately every three days until it ceased, about 30 DAP. At crop grain maturity, across all planting date by seeding rate treatment combinations, five pea plants in each plot were manually harvested for whole plant biomass, pods per plant, and seeds per plant to calculate yield component parameters. Harvest index was calculated by dividing the weight of the harvested seed per sample divided by the total whole plant biomass (seed yield $plant^{-1}$ / whole plant biomass $plant^{-1}$) for each sample. A plot combine (Zurn © 150 universal plot combine harvester, Zurn Harvesting GmbH & Co. KG) was used to harvest and collect data on grain yield, grain moisture, and test weight data for all 8 rows in each plot. In 2019, sites were desiccated with AIM EC® (a.i: carfentrazone-ethyl) at a rate of 98 ml ai $ha^{-1}$ on July 22, 2019 (Sidney) and July 25, 2019 (Hemingford) to improve harvestability. Location specific plot harvest and yield component sampling dates, which occurred on the same days, can be found in Table 1.

*Seedling Emergence Analysis*

Pea plant population versus PLS rate was analyzed in R 3.6.1 (R Core Team, 2018) using linear regression with lmer (Kuznetsova *et al*., 2017), lme4 (Bates *et al*., 2015a), and lmerTest packages (Kuznetsova *et al.*, 2017). Planting date and seeding rate were treated as fixed factors with replication and site-year treated as random. Interaction between planting

This article is protected by copyright. All rights reserved.

Accepted Article

date and seeding rate as explanatory variables was tested. If the interaction was non-significant, the main effects of treatments were evaluated.

Analysis of pea emergence against heat unit accumulation (GDD) was analyzed in R 3.6.1 (R Core Team, 2018) using *drc* (Ritz *et al*., 2015) and *tidyverse* (Wickham *et al.*, 2019) packages. Non-linear regression was completed using a sigmoid curve-dose response model. The best-fit dose response model was used to analyze emergence by planting date, site-year, year, or location. The best-fit model was chosen based on the lowest logistic likelihood using the *mselect* function in *drc* in R 3.6.1 (R Core Team, 2018). The upper limit was restricted to 100% emergence. A base temperature of 0° C was used to accumulate GDD units from the individual planting date treatment at each site-year for each emergence count observation. Based on the lowest logistic likelihood results, a Weibull model (Ritz, 2010; Ritz *et al*., 2015) was selected to describe the emergence pattern of explanatory variables:

Weibull curve (three parameters)

$$Y = d^{\#} \exp\{-\exp[\, b(\log x - e)]\} \qquad (1)$$

Weibull curve (four parameters)

$$Y = \mathrm{c} + (\mathrm{d} - \mathrm{c}) \exp\{-\exp[\, b(\log x - e)]\} \qquad (2)$$

where Y is the total seedling emergence at a specific cumulative heat unit, X is the specific accumulated heat unit on the day of observation, *d* is the higher asymptote, *c* is the lower asymptote, *e* is the specific amount of accumulated heat units needed to reach 50% cumulative field pea emergence, *b* is the slope around the inflection point. Shape parameters *d* and *c* were used to estimate the cumulative amount of heat units needed to reach 50% cumulative field pea emergence ($T_{50}$):

$$T_{50} = d/c \qquad (3)$$

This article is protected by copyright. All rights reserved.

Accepted Article

*Grain Yield Analysis*

Yield response and EOPP models as influenced by increasing plant populations within each planting date treatment and site-year were calculated using *AICcmodavg* (Mazerolle, 2017) and *drc* (Bates *et al*., 2015b) packages. Michaelis-Menten, two parameter asymptotic regression, linear, and quadratic models were compared for best-fit using AICc model selection in R 3.6.1 (R Core Team, 2018). Model selection indicated the two-parameter asymptotic regression model (AR2) should be used. For each AR2 model, a full, alpha, kappa, and reduced AR2 model was completed and selected based on AICc model selection and biological meaning. A germination rate of 90%, seed weight of 4631 seeds $kg^{-1}$, certified seed cost of \$0.55 $kg^{-1}$, and field pea market price of \$0.25 $kg^{-1}$ were used as model assumptions to calculate optimal plant population and partial net return for EOPP analysis. The AR2 model is as follows:

$$Y = \alpha \times (1 - e^{\left(-\frac{plant\ population}{kappa[planting\ date]}\right)}) \qquad (4)$$

where α is the maximum yield potential for the specific planting date treatment and kappa is the specific shape parameter for the specific planting date.

Based on the yield response from the AR2 model, partial input was calculated as the following:

$$\text{Partial input} = \frac{(plant\ population \times 1.1 \times 0.55 \times 10000)}{4631} \qquad (5)$$

where 1.1 is the adjustment for 90% emergence, 0.55 is the US\$ cost of certified seed $kg^{-1}$, 10000 is the adjustment from $m^2$ to hectares, and 4631 is the number of seeds $kg^{-1}$.

Partial net return was calculated using the yield response from the specific AR2 model using the following:

This article is protected by copyright. All rights reserved.

Accepted Article

$$\text{Partial net return} = (\text{Y} \times 0.25) - \text{Partial input} \quad (6)$$

where Y is the yield response unit for the specific planting date treatment from the best-fit AR2 model for the specific planting date treatment and 0.25 is the average value per kilogram of field pea grain in USD across five receiving points in Nebraska in 2018.

Yield component analyses were completed using linear regression in R 3.6.1 using lmer (Bates *et al*., 2015b). Planting date and seeding rate were treated as fixed factors with replication and site-year treated as random. Interaction was tested between treatment factors. If no interaction was present, only main effects of treatments were tested. Correlations among yield components were calculated using the CORR package in R 3.6.1 (R Core Team, 2018).

## RESULTS AND DISCUSSION

*Seedling Emergence*

Across all site – years, seeding rate did influence final plant populations ($P$ = <0.0001) (Table 2). The 77 and 99 PLS $m^{-2}$ seeding rates maximized plant density out of the five seeding rate treatments. Emergence over time among planting date treatments and site-years were different in order to reach either 50 or 90% emergence. This is due to faster accumulation of GDD units as planting is delayed into the spring. To reach 90% emergence, the late planting date required 130 (early planting) and 92 (middle planting) GDD units less that the two earlier planting dates (Figure 1) (Table 3). Figure 1 shows the increased rate of emergence over time when pea is planted later compared to the two earlier planting dates, due to greater cumulative GDD following planting.

Research suggests that percent emergence may decrease and seedling mortality increases with higher seeding rates (Johnston *et al.,* 2002; Gan *et al.*, 2003). However, Tawaha and Turk (2004) reported that increased seeding rates from 30 to 90 seeds $m^{-2}$ benefits plant development by reducing the time to 50% flowering. Additionally, previous studies show that as seeding rates increase, emergence rates can be decreased (Gan *et al.*,

This article is protected by copyright. All rights reserved.

Accepted Article

2003). Results from this experiment suggest that there is a yield advantage to increased seeding densities, even if percent emergence is reduced. Our results coincide with Meyer and Badaruddin (2001) as some planting date treatments in 2018 and 2019 at both sites were exposed to freeze events following establishment that reduced plant survival. Other research indicates that while earlier planting may reduce final plant density, a reduction in plant density due to frost injury is not as significant as the impact of high air temperatures and drought stress when the goal is maintaining yield potential (Tawaha and Turk, 2004; Miller *et al*., 2006a). In the presence of a growing season that exhibits maximum daily temperatures above 26° C, earlier planting overcomes decreased final stand density due to a greater retention of viable flowers (Bueckert *et al*., 2015).

Later planting tended to result in improved emergence rates as heat units were accumulated compared to the early or middle planting date (Figure 1). The difference between site-years and year suggests that seasonal climate and the inherent geographical differences between sites can influence emergence patterns in field peas across western Nebraska (Table 3). As spring planting conditions become more favorable to pea emergence, time to 50 and 90% emergence is reduced if later planting dates are utilized (Figure 1).

*Final Stand Density*

The two-way interactions of site – year with planting date and seeding rate indicated final plant density was not equal at all locations and among treatment combinations (Table 2). The presence of a site – year by seeding rate interaction ($P = 0.0002$) or site – year by planting date interaction ($P = 0.0030$) suggests that both planting date and seeding rate affect final plant density differently between sites. In 2018 at Hemingford, the middle planting date contained 16.2% more plants $ha^{-1}$ than the other planting dates. At Hemingford in 2019, the latest planting retained 17.9% more plants $m^{-2}$ compared to the early planting and 91.6%

This article is protected by copyright. All rights reserved.

Accepted Article

more plants than the middle planting across seeding rates. This difference was likely due to late spring blizzards (April 6-7, 2018 and March 12-13, 2019) that occurred following emergence (Table 4). At Sidney in 2018, the late planting date retained 12.5% more plants $m^{-2}$ than the middle planting date and 32.3% more plants $m^{-2}$ than the early planting date. In 2019 at Sidney, the late planting date retained 7.7% more plants $m^{-2}$ than the middle planting and 23.5% more plants $m^{-2}$ than the early planting date, a result of a spring hail event on May 27, 2019. Higher plant densities were observed in 2018 across all seeding rates compared to 2019 (Table 6). As noted by Puckridge and Donal (1967) and Fischer and Miles (1973), higher seeding rates can reduce percent emergence and result in a diminished stand density. As Sidney and Hemingford are different growing environments, seeding rates might influence final stand density differently between eco-regions (Tables 4, 5).

Linear regression analysis showed that planting date influenced the establishment rate of pea across varying seeding rates (Figure 2). Analysis across site-years showed that a later planting date resulted in a higher overall establishment rate for all seeding rates ($P = 0.0028$). The final plant establishment rate was identical among planting date treatments at Sidney in 2018 at 80 PLS $m^{-2}$. In 2019 at Sidney, planting date affected plant establishment rates across all seeding rates ($P = 0.0097$). For Hemingford in 2018 at the lowest seeding rate, the plant establishment rate was similar among planting dates treatments; however, as seeding rate increases, the April 12 planting date contained more plants $m^{-2}$ compared to the March 27 and March 14 planting dates. Across all planting dates and seeding rates at Hemingford in 2019, 76% of PLS $m^{-2}$ resulted in emerged plants. In general, knowing the rate of plant establishment as shown in Figure 2 will allow for precise selection of the EOPP, which will increase yield and optimize stand densities.

This article is protected by copyright. All rights reserved.

Accepted Article

*Grain Yield*

According to previous research, prolonged exposure of pea to high air temperatures decreases grain yield more than exposure to cold weather injury following emergence (Hwang *et al*., 2000; Tawaha and Turk, 2004; Allen *et al*., 2010; Fernandez *et al*., 2012). In many pea growing regions, altering planting dates to avoid heat stress exposure during flower development improves grain yield. However, the presence of early season freeze events at germination may mitigate any yield advantage associated with earlier planting in western Nebraska. Additionally, increased seeding rates may respond differently depending on the selected planting date. Thus, it is vital to show the possible dependency that seeding rate has on specific planting dates, in order to maximize grain yield with the most economically optimal plant population for specific western Nebraska sites.

The interactions of site – year with planting date and site – year with seeding rate for grain yield were significant ($P = 0.0002$, and $P = 0.0052$, respectively) (Table 2). Non-linear regression analysis during 2018 and 2019 showed that planting date and plant population influence overall yield and EOPP in a complex nature. Results from three site-years (Sidney 2018, Sidney 2019, and Hemingford 2018) showed that grain yield response curves vary among planting dates across increasing plant populations within a site-year. Yield response results (Figures 3 - 4) showed that the difference between environments does influence planting date, suggesting that planting date recommendations should be made on a site-specific basis. There were differences in grain yield between planting dates within a site-year (Figure 3). Across three site-years, planting date did not influence the maximum yield potential of field pea (Figure 4). However, the three planting dates did influence the shape parameter of the yield response curve as plant populations were increased within a site-year (Figure 3). Within a site-year, planting date did not influence the maximum yield potential of

This article is protected by copyright. All rights reserved.

Accepted Article

pea but did influence the shape parameter of grain yield response as plant population was increased (Figure 3).

Tawaha and Turk (2004) suggested that later planting reduced yield by 12% for every 14-day delay in planting. Results from this experiment suggest otherwise as yield response curves among planting dates show that later planting did not decrease yield. The discrepancy in results between this experiment and Tawaha and Turk (2004) might be due to the environmental differences between the Middle East and the Central Great Plains of North America as western Nebraska is classified as a BSk climate while northern Jordan in the Middle East is classified as a BSh under the Köppen Climate Classification (Beck *et al*., 2018). Varying plant populations influenced yield within specific sites and across all site-year observations in western Nebraska (Figures 3 - 4). In 2019 at Sidney, the response of yield to planting date and plant population showed that the April 24 planting promoted higher yields, followed by the March 27 and April 9 planting dates. Yield in 2018 at Sidney showed a different yield response with the March 26 planting generating higher yields (2831 kg $ha^{-1}$) compared to the March 12 (2601 kg $ha^{-1}$) and April 10 (2420 kg $ha^{-1}$) planting dates (Figure 3) across all observed plant population densities. The greatest difference in yield response across plant populations occurred between 40 – 80 plants $m^{-2}$ at most site-years. Yield response at Hemingford during 2018 showed less of a difference among planting dates across plant populations compared to Sidney. In 2018, Hemingford had a maximum yield potential across planting dates of 3039 kg $ha^{-1}$. Overall, the middle planting on March 27, 2018 in Hemingford resulted in the highest overall yield for that site-year, followed by the late (April 12) and early (March 14). Across the three site-years, Sidney 2018 produced the greatest grain yield (3296 kg $ha^{-1}$), followed by Hemingford 2018 (3039 kg $ha^{-1}$) and Sidney 2019 (2751 kg $ha^{-1}$).

This article is protected by copyright. All rights reserved.

Accepted Article

Pea grain yield responds positively to increased plant populations and a planting date that balances early and late season climate stresses such as late freeze events or high summer air temperatures. At most site-years, final plant populations above 100 plant $m^{-2}$ were almost always above the most beneficial EOPP and resulted in a diminishing yield return as plant populations increased above the specific EOPP for each planting date within a single site-year. This observation confirms findings of previous research that increased seeding rates above the EOPP result in a lower marginal return as final plant populations increase above the EOPP threshold. Because grain yield responses differ between sites and among planting dates due to varying plant populations, an optimal plant population should be targeted for each planting date. Although previous research has proven that high late season air temperatures decrease pea yield potential, this experiment showed that in most cases, later planting benefited pea grain yield in western Nebraska, due to an abnormally cool, wet growing seasons. Overall, later planting dates did not reduce grain yield, and in some instances at specific site-year observations such as Sidney 2018, later planting increased yield across plant populations (Figures 3-4).

*Primary Yield Components*

Linear regression found that plant population and planting date influenced yield components such as pods $plant^{-1}$ and seeds $plant^{-1}$ (Tables 2, 6)(Figures 5 - 6). Early planting exhibited a 5.2% increase in pods $plant^{-1}$, 7.8% increase in seeds $plant^{-1}$, and a 12.8% increase in the harvest index over late planting of field pea (Figure 6). However, the main effect of planting date only influenced harvest index (seed yield $plant^{-1}$ / whole plant biomass $plant^{-1}$) of pea (Table 6). This is a result of the plant responding to the decreased time to flowering, limiting the amount of non-grain biomass produced compared to earlier plantings (Figure 6). Seeding rate did influence biomass production and pods $plant^{-1}$, however harvest index

This article is protected by copyright. All rights reserved.

Accepted Article

remains relatively unchanged across seeding rates. Nleya and Rickertsen (2011) observed that in certain environments the harvest index can be decreased as seeding rate is increased. However, across all environments and pea varieties, harvest index and plant height remain unchanged, suggesting that planting date can influence harvest index, in addition to seeding rate. Any benefit of earlier planting to optimize harvest index did not translate to a benefit in grain yield when comparing yield response curves among planting date treatments (Figures 5 - 6). While only tested in 2018, plant height did not vary among seeding rates, which agrees with previous studies (Armstrong and Pate, 1994; Knott and Belcher, 1998; Pageau *et al*., 2007; Nleya and Rickertsen, 2011).

Most pea yield components were negatively correlated with final plant population as shown in this experiment. In 2018 at Sidney, results showed that seeds plant$^{-1}$ ($R^2$ = -0.81) and pods plant$^{-1}$ ($R^2$ = -0.70) had a strong negative correlation whereas seeds pod$^{-1}$ ($R^2$ = -0.41) had a weak negative correlation to increased plant populations (Figure 5). Results from Hemingford in 2018 and Sidney in 2019 displayed similar yield component relationships as Sidney in 2018. Although correlations between plant population, yield, and yield components from Hemingford were generally stronger in 2018 than 2019, all site-years showed that increased plant populations decreased yield components, especially pods plant$^{-1}$, even though grain yield was increased with increased plant populations. This observation across site-years alludes to the known physiological response of field pea to higher plant densities (Johnston *et al*., 2002; Gan *et al*., 2003; Tawaha and Turk, 2004; Nleya and Rickertsen, 2011). While grain yield is maintained or increased due to increased seeding rates, pea did not decrease seed production per pod, instead, pods plant$^{-1}$ are decreased to compensate for the higher plant density and increased competition for resources. This observation confirms that increased plant densities tend to limit pod formation the most

This article is protected by copyright. All rights reserved.

Accepted Article

compared to other yield components such as harvest index (Tawaha and Turk, 2004; De Bruin and Pedersen, 2008; Nleya and Rickertsen, 2011).

In previous studies across varying eco-regions, pea yield has been shown to increase with increased seeding rates while physiologically responding by reducing pods per plant (Johnston and Stevenson, 2001; Johnston *et al*., 2002; Gan *et al*., 2003; Tawaha and Turk, 2004; Nleya and Rickertsen, 2011). In addition, lower seeding rates were unable to increase branching and pods plant$^{-1}$ to match the increase in grain yield from increased plant populations. Increasing seeding rates that lead to higher plant populations increase grain yield, to a point, even though fewer pods per plant are produced. Increased grain yield per plant at low plant populations have been unable to match the yield advantage of higher plant populations that contained fewer seeds per plant (Johnston and Stevenson, 2001; Johnston *et al*., 2002; Gan *et al*., 2003; Tawaha and Turk, 2004; Nleya and Rickertsen, 2011).

The decrease in yield components does not decrease overall yield due to the yield advantage that more plants ha$^{-1}$ mitigates and overcomes the decrease in seed production per plant due to fewer pods per plant. Nleya and Rickertsen (2011) showed in a Northern Great Plains field pea study that yield components such as pods plant$^{-1}$ are significantly affected as seeding rate is varied, similar to findings in this experiment. Nleya and Rickertsen (2011) used a seeding rate treatment scheme of 25 – 90 seeds m$^{-2}$ , which is similar to the range of seeding rates used in this experiment. Similarly, Gan *et al.* (2003) observed significant differences in seedling emergence, grain yield, and grain size due to a seeding rate treatment scheme that resulted in a final stand density ranging from 35 – 80 plants m$^{-2}$, confirming that yield components are influenced by final plant population. Observations from previous studies support the general EOPP recommendations extrapolated from this experiment (70 – 109 plants m$^{-2}$), which can also indirectly increase harvestability due to tendril intertwining at

This article is protected by copyright. All rights reserved.

Accepted Article

higher plant populations. A higher seeding rate will increase yield until the yield plateau is reached (Figures 5 – 6). In general, the branching ability of pea at low populations does not result in increased grain yield compared to the yield advantage of higher populations.

*Economically Optimal Plant Population*

Planting at a higher seeding rate to maximize yield is not always the best financial decision due to a diminishing return on investment as seeding rates increased. However, higher seeding rates may be needed, depending on the specific planting date chosen. The economically optimal plant population (EOPP) is the plant population that maximizes return on investment, which in this experiment is driven by seed cost (excluding the cost of rhizobia inoculum and other seed treatments). The EOPP in this case is dependent on assumptions such as a fixed germination rate, seed weight, seed cost, and pea grain market price. These assumptions were constant throughout the analysis in order to focus on the key variables of planting date and seeding rate but should be taken into consideration when formulating seeding rates at individual operation. Obtaining a reliable EOPP is dependent upon the relative planting date chosen and specific growing region.

Economically optimal seeding rates did change as planting date is varied within a single site-year (Figure 7). EOPP results from Sidney in 2018 demonstrated a partial net return ($ $ha^{-1}$) of $682.70 for the middle planting whereas the early ($655.96) and late ($617.27) planting date treatments displayed lower partial net return (Figure 7). To achieve maximum yield in 2018 at Sidney, the early and late planting dates required a higher plant population, thus increasing seed costs for those planting dates (Figure 2). At Hemingford in 2018, results showed that maximum partial return is attained at 70 plants $m^{-2}$ for the middle planting followed by 74 plants $m^{-2}$ and 83 plants $m^{-2}$ for the late and early planting dates. By planting on March 27 with a final population of 70 plants $m^{-2}$ compared to planting on March

This article is protected by copyright. All rights reserved.

Accepted Article

14 at 83 plants $m^{-2}$, partial net return was increased by 25.00 \$ $ha^{-1}$ at Hemingford in 2018. The increase in seeding rate for later plantings is needed to compensate for a shortened flowering period and lengthier exposure to high temperatures during reproductive stages typically the later peas are planted in the spring. Additionally, linear regression showed that later planting across the three site-years increased percent emergence and magnitude of stand development, which resulted in diminished seed costs to obtain the same EOPP when planting later (Figure 2). According to 2018 results, seeding rates for pea should be increased to increase final stand density by approximately 44 plants $m^{-2}$ over what Stepanovic *et al.* (2018) found to be the EOPP from 2015 and 2016 site-year data collected in west-central Nebraska. To obtain the EOPP for a specific site, the seeding rate should be adjusted based on the establishment rate for each individual planting date. As an example, if a producer wants to target an EOPP of 75 plants $m^{-2}$ for an early planting timing, the PLS $m^{-2}$ that should be targeted would be 105 PLS $m^{-2}$, based on establishment results from this experiment at Sidney and Hemingford (Figure 2). The differences in EOPP and seeding rate recommendations between western Nebraska pea studies is possibly due to site-specific differences between research sites used in Stepanovic *et al.* 2018 (Grant, NE) and this experiment (Sidney & Hemingford, NE), as well as site-specific growing season weather among the four different years compared between Stepanovic *et al.* (2018) and this experiment, in addition to the discrepancy in planting dates between studies. EOPP specific to planting date is relevant to individual site-years, however, EOPP did not vary by planting dates across multi-site-year analysis (Figures 7 - 8).

Previous studies have shown that optimizing seeding rate within a specific eco-region can drastically improve grain yield and yield components in field pea (Johnston *et al*., 2002; Gan *et al*., 2003; Tawaha and Turk, 2004; Hwang *et al*., 2006; Nleya and Rickertsen, 2011; Stepanovic *et al*., 2018). The significant interaction of site-year with planting date and

This article is protected by copyright. All rights reserved.

Accepted Article

seeding rate alludes to the importance of developing planting date and seeding rate recommendations through EOPP models specific to each unique eco-region in western Nebraska for multiple plantings dates. In most observations the EOPP between site-years that resulted in the highest net return fell between 80 – 100 plants $m^{-2}$. Across all site-years, EOPP was only slightly influenced by planting date, with EOPP varying only 4 plants $m^{-2}$ between the middle planting (109 plants $m^{-2}$) and the early or late planting (105 plants $m^{-2}$). This result suggests that from an economic perspective, producers that grow peas in a variety of environments across western Nebraska may not need to always plant field pea in mid-March as EOPP can be adjusted to meet earlier or later planting dates during the spring. This experiment suggests that variations in site-year climate influence yield response as the maximum yield was decreased by 169 kg $ha^{-1}$ at Sidney from 2018 to 2019 and between Hemingford and Sidney in 2018. Overall, plant populations greater than 70 plants $m^{-2}$ and below the highest EOPP of 109 plants $m^{-2}$ should be targeted, regardless of planting timing in western Nebraska to maximize partial net return while maintaining yield.

## CONCLUSION

The choice of planting date and seeding rate of pea are important management decisions that influence emergence, yield, yield components, and other physiological characteristics. Across all site-year combinations, plant population, a function of seeding rate, was the most influential explanatory variable, as shown in the yield response curves. Additionally, planting date was shown to not influence yield response curves when overall yield data was averaged across all site-years. Planting pea in early to mid-March increased yield and partial net return compared to later planting within individual site-years (Sidney and Hemingford in 2018). Overall yield across environments was not decreased due to later planting, thus earlier planting might not be optimal as rate of establishment is decreased in

This article is protected by copyright. All rights reserved.

Accepted Article

earlier plantings. Emergence is prolonged when planting earlier as early spring freeze events slow the accumulation of GDD. While emergence is prolonged when planting earlier, overall EOPP results show that different emergence patterns do not necessarily result in a partial net return or yield difference among planting dates. A plant population of approximately 70 - 109 plants $m^{-2}$ is needed to optimize yield and partial net return. Higher seeding rates tend to increase yield, even though some yield component parameters are reduced, such as pods $plant^{-1}$. The decrease in yield components did not influence the yield advantage of increasing seeding rates to increase final plant densities. However, yield components did describe the physiological response of pea to different seeding rates and slight environment conditions.

A holistic approach should be followed for pea planting if farmers are planting yellow pea across multiple eco-regions and throughout the spring season as yield can be influenced by environment, planting date, and seeding rate. Planting during late March optimized yield for 2 of 3 site-years (Hemingford and Sidney in 2018), suggesting that balancing stresses of early spring cold and early summer heat results in optimized yield. Overall, adjusting PLS rates to attain an EOPP between 70 – 109 plants $m^{-2}$ for the specific eco-region is an ideal combination to maximize yield and partial net return if paired with a planting date that targets late-March.

## ACKNOWLEDGEMENTS:

This study was funded by North-Central Sustainable Agriculture Research and Education program (NC-SARE). We are grateful for the effort and dedication that was invested by Jake Hansen, James Burford, Bill Struckmeyer, Luana Machado, Juliano Sulzback, Matheus Torres Goncalves, Guilherme Chudzik, Zaim Ugljic, and Nemanja Cone Arsenijevic throughout the entirety of this project from planting to harvest, sample processing, and data interpretation.

This article is protected by copyright. All rights reserved.

Accepted Article

## REFERENCES

3.6.1., R.D.C.T. 2018. A Language and Environment for Statistical Computing. R Found. Stat. Comput. 2: https://www.R-project.org. http://www.r-project.org.

Adderley, D.R., J.J. Schoenau, R.A. Holm, and P. Qian. 2006. Nutrient availability and yield of wheat following field pea and lentil in Saskatchewan, Canada. J. Plant Nutr. 29(1): 25–34. doi: 10.1080/01904160500416430.

Allen, B., A. Lenssen, U. Sainju, T. Caesar, R. Lartey, *et al*. 2010. Management Strategies to Improve Yield and Nitrogen Use of Spring Wheat and Field Pea in the Semi-Arid Northern Great Plains USA . World (August): 133–136.

Amrstrong, E.L., and J.S. Pate. 1994. The field pea crop in S.W. Australia. I.Patterns of growth, biomass production and photosynthetic performance in genotypes of contrasting morphology. Aust. J. Agric. Res. 45(7): 1347–1362.

Anderson, R.L., R.A. Bowman, D.C. Nielsen, M.F. Vigil, R.M. Aiken, *et al*. 1999. Alternative crop rotations for the central Great Plains. J. Prod. Agric. 12(1): 95–99. doi: 10.2134/jpa1999.0095.

Baird, J.M., S.J. Shirtliffe, and F.L. Walley. 2009. Optimal seeding rate for organic production of lentil in the northern Great Plains. Can. J. Plant Sci. 89(6): 1089–1097. doi: 10.4141/CJPS08226.

Bates, D., M. Machler, B. Bolker, and S. Walker. 2015a. Fitting Linear Mixed-Effects Models using Lme4. : 1--48. doi: 10.18637/jss.v067.i01.

Bates, D., M. Mächler, B.M. Bolker, and S.C. Walker. 2015b. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67(1). doi: 10.18637/jss.v067.i01.

Beck, H.E., N.E. Zimmermann, T.R. McVicar, N. Vergopolan, A. Berg, *et al*. 2018. Present and future köppen-geiger climate classification maps at 1-km resolution. Sci. Data 5: 1–12. doi: 10.1038/sdata.2018.214.

De Bruin, J.L., and P. Pedersen. 2008. Soybean seed yield response to planting date and seeding rate in the upper midwest. Agron. J. 100(3): 696–703. doi: 10.2134/agronj2007.0115.

Bueckert, R.A., S. Wagenhoffer, G. Hnatowich, and T.D. Warkentin. 2015. Effect of heat and precipitation on pea yield and reproductive performance in the field. Can. J. Plant Sci. 95(4): 629–639. doi: 10.4141/cjps-2014-342.

Dhuyvetter, K.C., C.R. Thompson, C.A. Norwood, and A.D. Halvorson. 1996. Economics of Dryland Cropping Systems in the Great Plains: A Review. Jpa 9(2): 216. doi: 10.2134/jpa1996.0216.

Fernandez, A.L., C.C. Sheaffer, D.L. Wyse, and T.E. Michaels. 2012. Yield and weed

This article is protected by copyright. All rights reserved.

Accepted Article

abundance in early- and late-sown field pea and lentil. Agron. J. 104(4): 1056–1064. doi: 10.2134/agronj2012.0031.

Fischer, R.A., and R.E. Miles. 1973. The role of spatial pattern in the competition between crop plants and weeds. a theoretical analysis. Math. Biosci. 18(3–4): 335–350. doi: 10.1016/0025-5564(73)90009-6.

French, R.J. 1990. The contribution of pod numbers to field pea (Pisum sativum L.) yields in a short growing-season environment. Aust. J. Agric. Res. 41(5): 853–862. doi: 10.1071/AR9900853.

Gan, Y.T., P.R. Miller, B.G. McConkey, R.P. Zentner, P.H. Liu, *et al*. 2003. Optimum plant population density for chickpea and dry pea in a semiarid environment. Can. J. Plant Sci. doi: 10.4141/P02-012.

Hwang, S.F., R.L. Conner, K.F. Chang, B.D. Gossen, H. Su, *et al*. 2006. Impact of seeding rate and depth on mycosphaerella blight and seed yield of field pea. Can. J. Plant Sci. doi: 10.4141/P05-023.

Hwang, S.F., B.D. Gossen, G.D. Turnbull, K.F. Chang, R.J. Howard, *et al*. 2000. Seeding date, temperature, and seed treatment affect Pythium seedling blight of field pea. Can. J. Plant Pathol. 22(4): 392–399. doi: 10.1080/07060660009500458.

Johnston, A.M., G.W. Clayton, G.P. Lafond, K.N. Harker, T.J. Hogg, *et al*. 2002. Field pea seeding management. Can. J. Plant Sci. 82(4): 639–644. doi: 10.4141/P02-001.

Johnston, A.M., and F.C. Stevenson. 2001. Field pea response to seeding depth and P fertilization. Can. J. Plant Sci. 81(3): 573–575. doi: 10.4141/P00-166.

Joshi, P.K., and P.P. Rao. 2017. Global pulses scenario: status and outlook. Ann. N. Y. Acad. Sci. 1392(1): 6–17. doi: 10.1111/nyas.13298.

Knott, C.M., and S.J. Belcher. 1998. Optimum sowing dates and plant populations for winter peas (Pisum sativum). J. Agric. Sci. 131(4): 449–454. doi: 10.1017/S0021859698005991.

Kuznetsova, A., P.B. Brockhoff, and R.H.B. Christensen. 2017. lmerTest Package: Tests in Linear Mixed Effects Models . J. Stat. Softw. 82(13): 1–26. doi: 10.18637/jss.v082.i13.

Mazerolle, M.J. 2017. AICcmodavg: model selection and multimodel inference based on (Q)AIC(c). R Packag. version 2.1-1 R package(R Packag. version 2.1-1): R Packag. version 2.1-1. https://cran.r-project.org/package=AICcmodavg.

Meyer, D.W., and M. Badaruddin. 2001. Frost tolerance of ten seedling legume species at four growth stages. Crop Sci. 41(6): 1838–1842. doi: 10.2135/cropsci2001.1838.

Miller, P.R., S.A. Brandt, C.L. McDonald, and J. Waddington. 2006a. Chickpea, lentil, and pea response to delayed spring seeding on the Northern Great Plains. Can. J. Plant Sci. 86(4): 1059–1070. doi: 10.4141/P05-243.

Miller, P.R., R.E. Engel, and J.A. Holmes. 2006b. Cropping sequence effect of pea and pea management on spring wheat in the northern Great Plains. Agron. J. 98(6): 1610–1619.

This article is protected by copyright. All rights reserved.

Accepted Article

doi: 10.2134/agronj2005.0302.

Miller, P.R., Y. Gan, B.G. McConkey, and C.L. McDonald. 2003. Pulse crops for the Northern Great Plains. Agron. J. 95(4): 980. doi: 10.2134/agronj2003.0980.

Miller, P.R., J. Waddington, C.L. McDonald, and D.A. Derksen. 2002. Cropping sequence affects wheat productivity on the semiarid northern Great Plains. Can. J. Plant Sci. 82(2): 307–318. doi: 10.4141/P01-116.

Nleya, T., and J. Rickertsen. 2011. Seeding Rate and Variety Effects on Yield , Yield Components, and Economic Return of Field Pea in the Northern Great Plains Crop Management. Crop Manag. (February). doi: 10.1094/CM-2011-0221-01-RS.Abstract.

Oelke, E., E. Oplinger, and C. Hanson. 1991. Dry field pea. Altern. Crop. Manual. …. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Dry+Field+Pea#2 (accessed 19 April 2018).

Pageau, D., J. Lajeunesse, and J. Lafond. 2007. Effect of seeding rate on productivity of dry pea under cool climate. Can. J. Plant Sci. 87(1): 41–48. doi: 10.4141/p06-057.

Pavek, P.L.S. 2012. Plant Guide for pea (Pisum sativum L.). USDA-Natural Resour. Conserv. Serv. Pullman, WA.: 1–6. https://plants.usda.gov/plantguide/pdf/pg_pisa6.pdf (accessed 19 April 2018).

Puckridge, D.W., and C.M. Donal. 1967. Competition among wheat plants sown at a wide range of densities. Aust. J. Agric. Res. 18(2): 193–211. doi: 10.1071/AR9670193.

Querard, J., T.Z. Markus, M.A. Plamont, C. Gauron, P. Wang, *et al*. 2015. Photoswitching kinetics and phase-sensitive detection add discriminative dimensions for selective fluorescence imaging. Angew. Chemie - Int. Ed. 54(9): 2633–2637. doi: 10.1002/anie.201408985.

Ritz, C. 2010. Toward a unified approach to dose-response modeling in ecotoxicology. Environ. Toxicol. Chem. 29(1): 220–229. doi: 10.1002/etc.7.

Ritz, C., F. Baty, J. Streibig, and D. Gerhard. 2015. Dose Response Analysis using R. http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0146021.

Schatz, B., and G. Endres. 2009. Field pea production A-1166 (revised). NDSU Ext. Serv. 1166(MARCH 2003): 1–8.

Stepanovic, S. V., C. Burr, J.A. Peterson, D. Rudnick, C.F. Creech, *et al*. 2018. Field pea response to seeding rate, depth, and inoculant in west-central Nebraska. Agron. J. 110(4): 1412–1419. doi: 10.2134/agronj2017.10.0600.

Tanaka, D.L., J.M. Krupinsky, M.A. Liebig, S.D. Merrill, R.E. Ries, *et al*. 2002. Dynamic cropping systems: An adaptable approach to crop production in the Great Plains. Agron. J. 94(5): 957–961. doi: 10.2134/agronj2002.9570.

Tawaha, A.M., and M.A. Turk. 2004. Field pea seeding management for semi-arid Mediterranean conditions. J. Agron. Crop Sci. doi: 10.1046/j.1439-037X.2003.00079.x.

This article is protected by copyright. All rights reserved.

Accepted Article

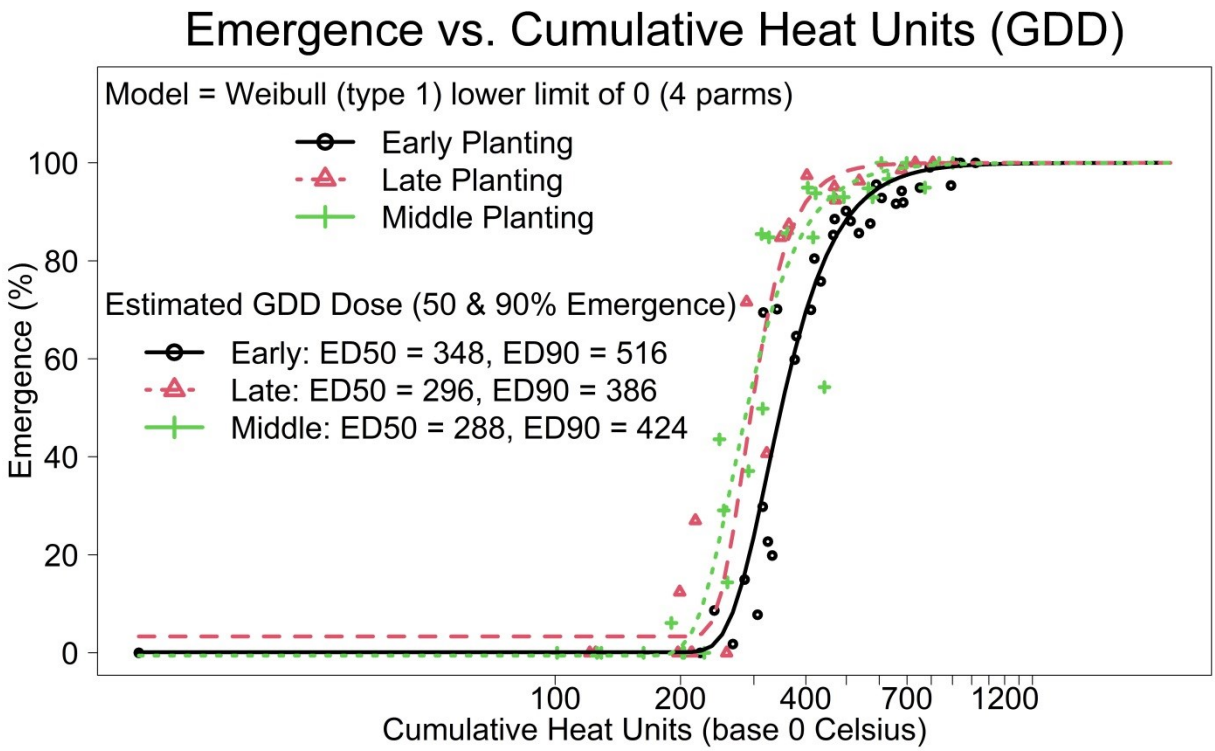
USA Dry Pea & Lentil Council. 2018. 2018 NASS Prospective Planting Report. : 1–3.

Welbaum, G.E., D. Bian, D.R. Hill, R.L. Grayson, and M.K. Gunatilaka. 1997. Freezing tolerance, protein composition, and abscisic acid localization and content of pea epicotyl, shoot, and root tissue in response to temperature and water stress. J. Exp. Bot. 48(3): 643–654. doi: 10.1093/jxb/48.3.643.

Wickham, H., M. Averick, J. Bryan, W. Chang, L. McGowan, *et al*. 2019. Welcome to the Tidyverse. J. Open Source Softw. 4(43): 1686. doi: 10.21105/joss.01686.

**Figure Captions**

FIGURE 1. Field pea percent emergence across four site-years as determined by cumulative heat units accumulated from the day of planting for each specific planting date using a sigmoid curve dose response model. Slopes between planting date treatments were different except at the paired comparison between early and middle planting dates. The needed heat units to reach 50 and 90% emergence were different between planting date treatments as shown above.




This article is protected by copyright. All rights reserved.

Accepted Article

FIGURE 2. Linear regression of observed plant population against PLS across three plantings dates and five seeding rates at three site-years. The absence of an interaction between seeding rate and planting date suggests that the establishment rate of gain was not different.

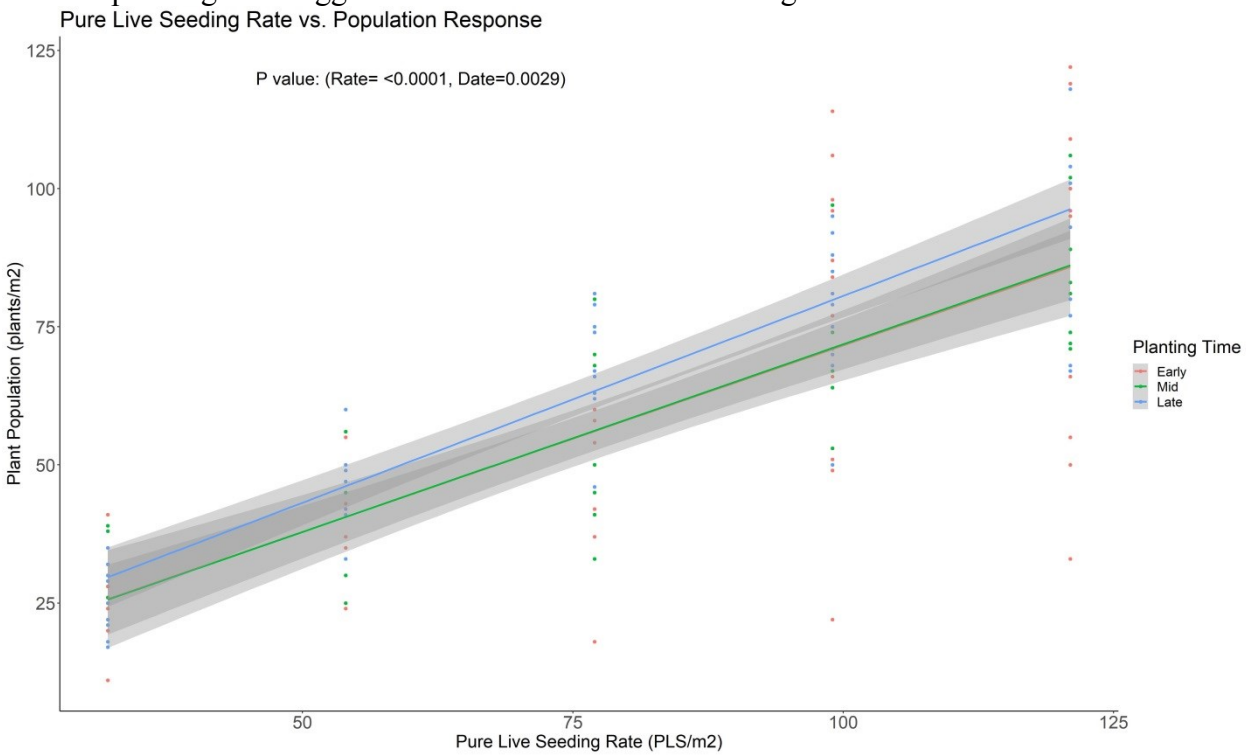
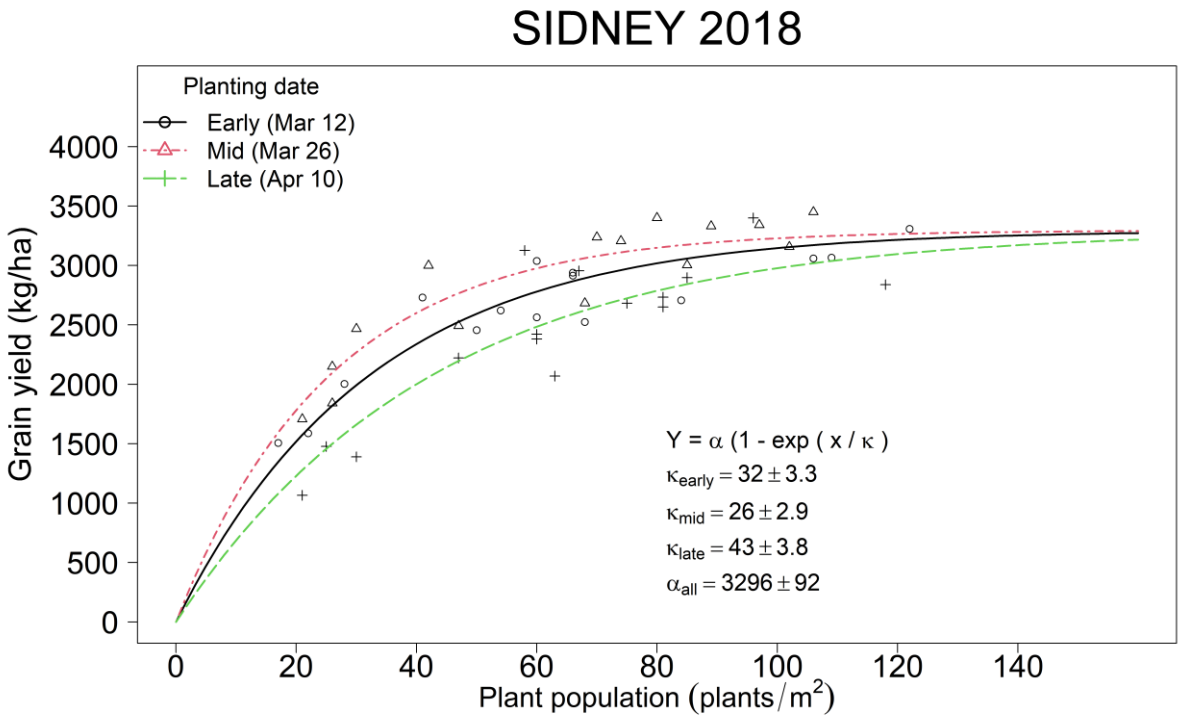



FIGURE 3. Yield response of field pea in 2018 as determined by planting date and final plant population at Sidney, NE following a kappa model in two-parameter asymptotic regression.




This article is protected by copyright. All rights reserved.

Accepted Article

FIGURE 4. Yield response of field pea following a kappa model in two-parameter asymptotic regression model across three site-years as determined by planting date and final plant population at Sidney, NE (2018 & 2019) & Hemingford, NE (2019).

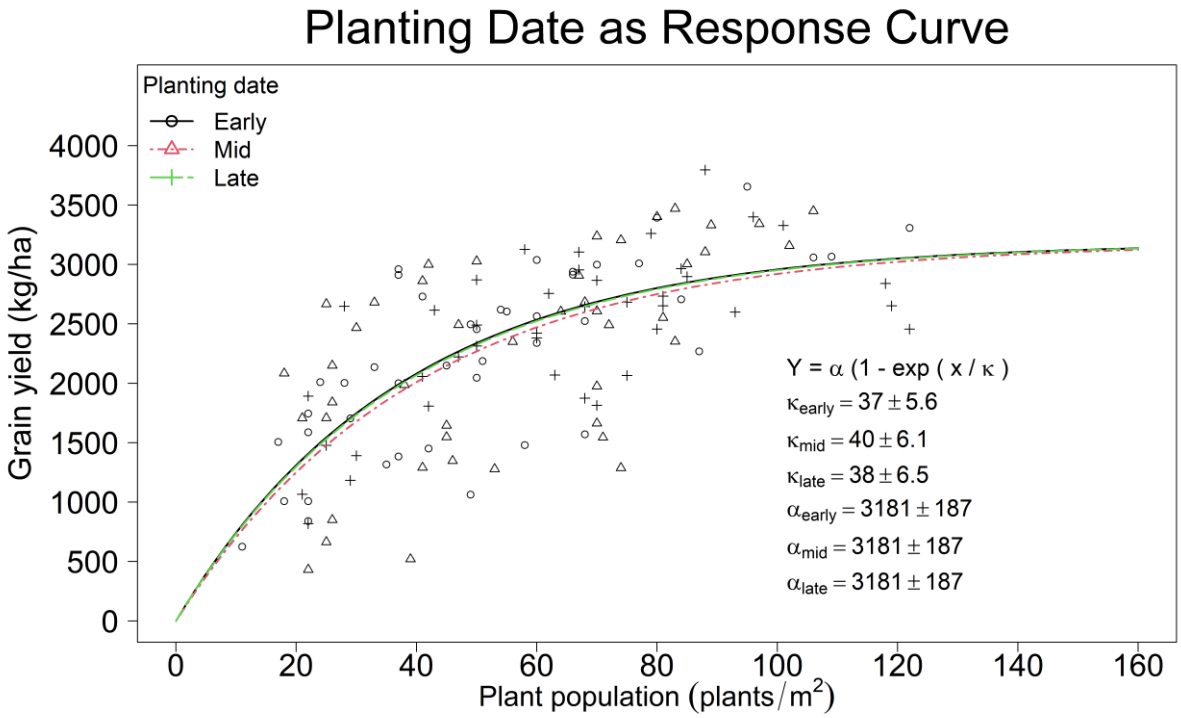
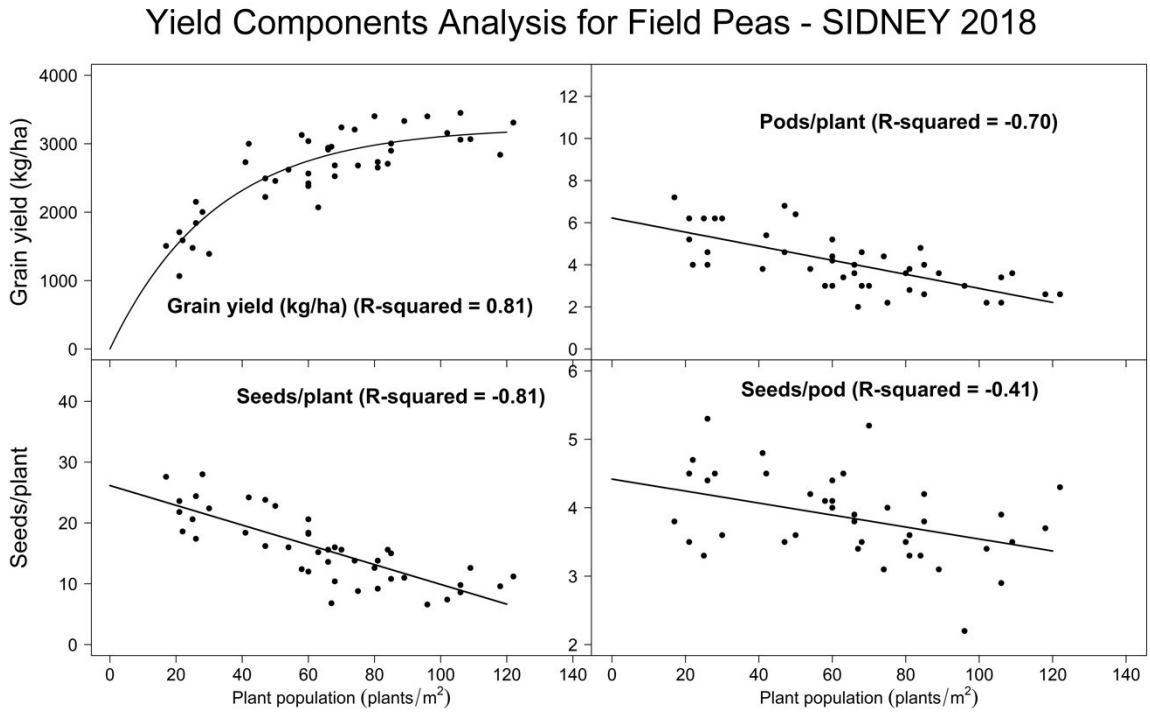



FIGURE 5. Yield and yield component response across plant populations for Sidney, NE in 2018 with the corresponding coefficient of determination results for each response variable.




This article is protected by copyright. All rights reserved.

Accepted Article

FIGURE 6. Influence of planting date on grain yield, pods plant$^{-1}$, seeds plant$^{-1}$, and harvest index across increasing plant populations in three site-years (Sidney 2018 & 2019, Hemingford 2019) in western Nebraska.

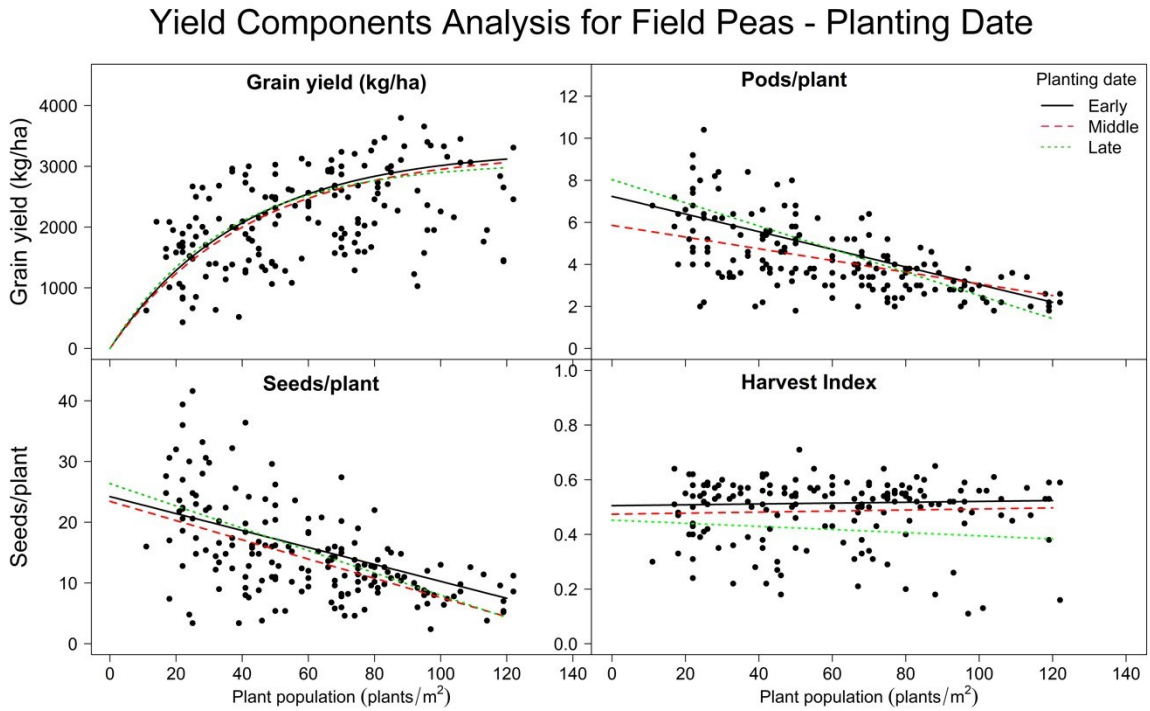
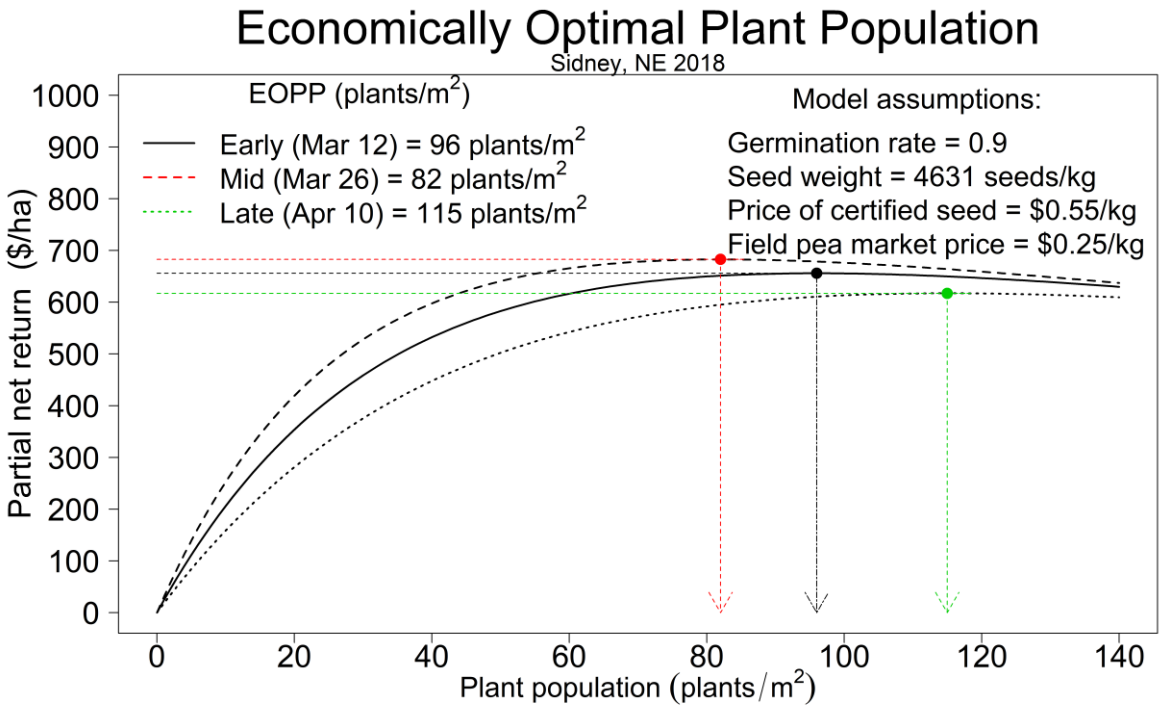


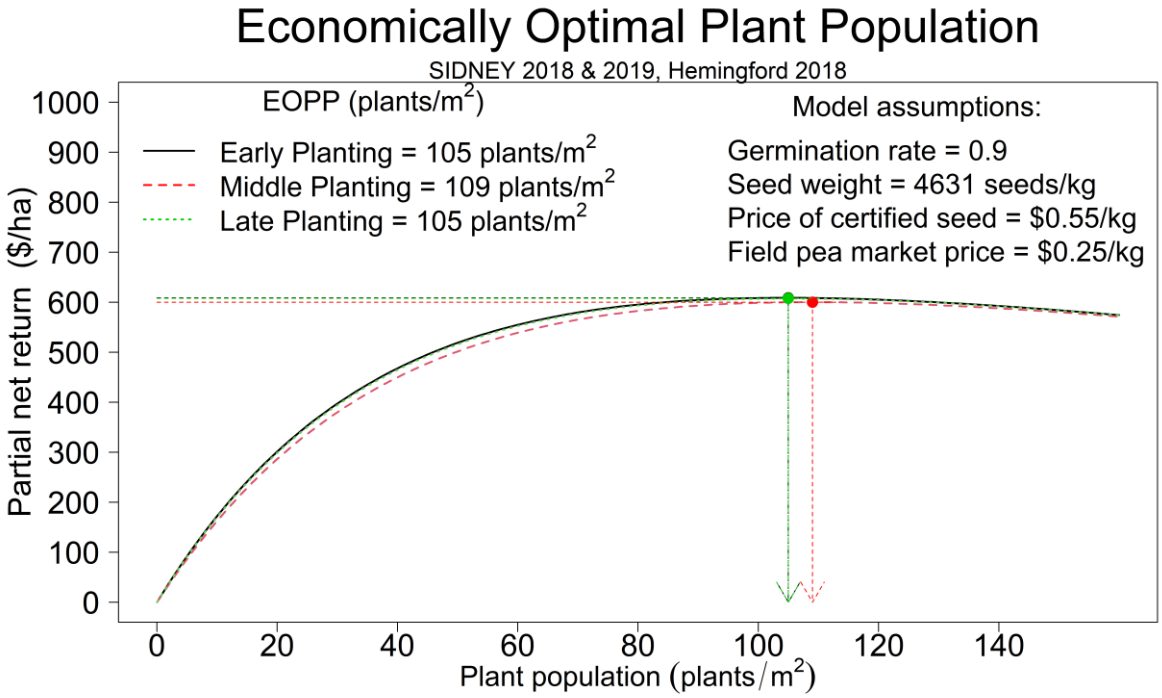

FIGURE 7. Economically Optimal Plant Population (EOPP) as a function of planting date, plant population, yield response, and economic model assumptions from Sidney, NE in 2018.




This article is protected by copyright. All rights reserved.

Accepted Article

FIGURE 8. Economically Optimal Plant Population (EOPP) as a function of planting date, final plant population, and economic model assumptions such as field pea market price and certified seed costs at Sidney, NE in 2018 & 2019 and Hemingford, NE in 2018.




## TABLES

TABLE 1. Year of experiment, planting dates, and harvest dates for Sidney and Hemingford for 2018 and 2019 in western Nebraska.

| Location and Plant Date | Planting Date | | Harvest Date† | |
|---|---|---|---|---|
| | 2018 | 2019 | 2018 | 2019 |
| Sidney | | | | |
| Early | 12 March | 27 March | 10-Jul | 30-Jul |
| Middle | 26 March | 8 April | 10-Jul | 30-Jul |
| Late | 10 April | 24 April | 10-Jul | 30-Jul |
| Hemingford | | | | |
| Early | 14 March | 8 April | 20-Jul | 7-Aug |
| Middle | 27 March | 24 April | 20-Jul | 7-Aug |
| Late | 12 April | 13 May | 20-Jul | 7-Aug |

† Yield component sampling was completed on the same day prior to whole plot harvest

This article is protected by copyright. All rights reserved.

Accepted Article

TABLE 2. Significance of main and interaction effects of environment (site x year), planting date, and seeding rate across on grain yield, yield components, and final stand density.

| Source of Variation (SV) | Yield kg $ha^{-1}$ | Plant Biomass grams | Pods $plant^{-1}$ | Seeds $pod^{-1}$ | Seeds $plant^{-1}$ | Harvest Index % | Final Plant Density plant $ha^{-1}$ |
|---|---|---|---|---|---|---|---|
| Site - Year (SY) | 0.0002 | 0.39 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| Planting Date (D) | 0.79 | 0.49 | 0.0016 | 0.06 | 0.001 | <0.0001 | 0.14 |
| Seeding Rate (R) | <0.0001 | 0.001 | <0.0001 | <0.0001 | <0.0001 | 0.83 | <0.0001 |
| SY x D | 0.0001 | 0.35 | 0.0383 | 0.29 | 0.0562 | 0.0095 | 0.0031 |
| SY x R | 0.0052 | 0.054 | 0.0004 | 0.11 | <0.0001 | 0.0214 | 0.0002 |
| D x R | 0.37 | 0.53 | 0.45 | 0.09 | 0.41 | 0.79 | 0.23 |
| SY x D x R | 0.94 | 0.06 | 0.48 | 0.56 | 0.23 | 0.66 | 0.20 |

† significance of treatment effects and interactions were evaluated at $\alpha = 0.05$.

TABLE 3. Cumulative heat units needed to reach 50 % and 90 % emergence of field pea for four site-years across all planting dates in western Nebraska.

| Site-Year | Cumulative Heat Units (base 0 Celsius) | Std. Error |
|---|---|---|
| Hemingford - 2018 | | |
| 50% Emergence | 336 | 1 |
| 90% Emergence | 383 | 4 |
| Hemingford - 2019 | | |
| 50% Emergence | 299 | 3 |
| 90% Emergence | 430 | 14 |
| Sidney - 2018 | | |
| 50% Emergence | 346 | 3 |
| 90% Emergence | 493 | 10 |
| Sidney - 2019 | | |
| 50% Emergence | 281 | 3 |
| 90% Emergence | 450 | 9 |

This article is protected by copyright. All rights reserved.

Accepted Article

TABLE 4. Final plant density (plants $m^{-2}$) of field pea as influenced by three planting dates across four site-years in western Nebraska from 2018 and 2019 experiments.

| Location | Year | Planting Date Treatment | | | | | |
|---|---|---|---|---|---|---|---|
| | | Early | | Middle | | Late | |
| | | Estimate | SE | Estimate | SE | Estimate | SE |
| | | plants $m^{-2}$ | | | | | |
| Sidney† | 2018 | 34 | 5 | 40 | 6 | 45 | 5 |
| Sidney†† | 2019 | 34 | 4 | 39 | 3 | 42 | 4 |
| Hemingford† | 2018 | 38 | 4 | 43 | 4 | 38 | 5 |
| Hemingford‡ | 2019 | 39 | 6 | 24 | 5 | 46 | 5 |

† Sidney 2018: Early (March 12), Middle (March 26), Late (April 10)
†† Sidney 2019: Early (March 27), Middle (April 8), Late (April 24)
† Hemingford 2018: Early (March 14), Middle (March 27), Late (April 12)
‡ Hemingford 2019: Early (April 8), Middle (April 24), Late (May 13)

TABLE 5. Final plant density (plants $m^{-2}$) of field pea across four site-year combinations in western Nebraska in 2018 and 2019 as influenced by five seeding rates (PLS $ha^{-1}$) .

| Site | Year | Seeding Rate Treatment | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 321,000 | | 543,000 | | 765,000 | | 988,000 | | 1,210,000 | |
| | | Estimate | SE | Estimate | SE | Estimate | SE | Estimate | SE | Estimate | SE |
| Sidney† | 2018 | 21 | 3 | 39 | 7 | 52 | 7 | 56 | 20 | 32 | 29 |
| Sidney†† | 2019 | 21 | 6 | 30 | 6 | 39 | 12 | 49 | 9 | 54 | 9 |
| Hemingford† | 2018 | 24 | 5 | 35 | 7 | 43 | 11 | 55 | 14 | 42 | 27 |
| Hemingford‡ | 2019 | 21 | 9 | 33 | 13 | 49 | 20 | 46 | 31 | 33 | 32 |

† Sidney 2018: Early (March 12), Middle (March 26), Late (April 10)
†† Sidney 2019: Early (March 27), Middle (April 8), Late (April 24)
† Hemingford 2018: Early (March 14), Middle (March 27), Late (April 12)
‡ Hemingford 2019: Early (April 8), Middle (April 24), Late (May 13)

TABLE 6. Linear regression analysis on the effect of planting date and plant population on pods $plant^{-1}$, seeds $plant^{-1}$, and harvest index of field pea across three site-years in western Nebraska in 2018 and 2019.

| Source of Variation (SV) | df | Pods $plant^{-1}$ | df | Seeds $plant^{-1}$ | df | Harvest Index |
|---|---|---|---|---|---|---|
| | | p-value | | p-value | | p-value |
| Plant Population | 128.9 | <0.0001 | 127 | <0.0001 | 128.5 | 0.045 |
| Planting Date | 123.3 | 0.49 | 123 | 0.51 | 128 | <0.0001 |

† Significance of treatment effects were evaluated at $\alpha = 0.05$.

This article is protected by copyright. All rights reserved.