

Pea Growth, Yield, and Quality in Different Crop Rotations and Cultural Practices

Upendra M. Sainju,* Andrew W. Lenssen, Brett L. Allen, Jalal D. Jabro, and William B. Stevens

Core Ideas

- Management strategies are lacking to enhance dryland pea growth, yield, and quality.
- Pea yield and quality were studied in various crop rotations and cultural practices.
- Pea yield and N uptake were greater with alternate-year than stacked crop rotation.
- Stand count was greater with the improved than the traditional cultural practice.
- Alternate-year rotation and improved cultural practice enhanced pea yield and quality.

U.M. Sainju, B.L. Allen, J.D. Jabro, and W.B. Stevens, USDA-ARS, Northern Plains Agricultural Research Lab., Sidney, MT 59270; and A.W. Lenssen, Dep. of Agronomy, Iowa State Univ., Ames, IA 50011. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by USDA. The USDA is an equal opportunity employer.

Received 1 Oct. 2018.

Accepted 19 Mar. 2019.

*Corresponding author (upendra.sainju@ars.usda.gov).

Agrosyst. Geosci. Environ. 2:180041 (2019)
doi:10.2134/age2018.10.0041

ABSTRACT

Dryland pea (*Pisum sativum* L.) is an important pulse crop that can replace fallow or be added to existing crop rotations to sustain crop yields in arid and semiarid regions. Yet, we lack management practices to enhance yield and quality of dryland pea. This study evaluated the effect of crop rotation and cultural practices on dryland pea growth, yield, and quality from 2006 to 2011 in the northern Great Plains, USA. Stacked rotations were durum (*Triticum turgidum* L.)–durum–canola (*Brassica napus* L.)–pea (DDCP) and durum–durum–flax (*Linum usitatissimum* L.)–pea (DDFP), and alternate-year rotations were durum–canola–durum–pea (DCDP) and durum–flax–durum–pea (DFDP). Traditional cultural practice included a combination of conventional till, recommended seed rate, broadcast N fertilization, and reduced stubble height, and improved cultural practice a combination of no-till, increased seed rate, banded N fertilization, and increased stubble height. Pea pod number, plant height, grain yield, and N uptake were 4 to 18% greater with DCDP and DDCP than other rotations. Improved cultural practice increased stand count by 29% over traditional cultural practice. Biomass yield, N uptake, and grain protein concentration varied with crop rotations and cultural practices in various years. Seed number, seed weight, harvest index, and N harvest index were not influenced by treatments. Pea yield and N uptake increased with alternate-year rotation due to increased pod number and plant height. Stand count increased with improved cultural practice. Alternate-year crop rotations and improved cultural practice enhanced dryland pea yield and quality.

Abbreviations: DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea; DFDP, durum–flax–durum–pea.

Pea (*Pisum sativum* L.) requires little water to grow, and therefore, provides an important pulse crop in dryland cropping systems (Tanaka et al., 2010; Miller et al., 2015; Lenssen et al., 2018). Pea supplies protein and fiber for human and livestock diets (Hood-Nieffer et al., 2012), particularly for vegetarian people in developing countries with limited protein sources (Tzitzikas et al., 2006; Hood-Nieffer et al., 2012) and acts as a starch source widely used in processing noodles (Ratnayake et al., 2002; Tan et al., 2009). From a soil fertility perspective, pea fixes more N from the atmosphere than lentil (*Lens culinaris* L.) and cowpea (*Vigna unguiculata* L.) (Miller et al., 2003b) and needs little P or K fertilizer to grow than other legumes (Tzitzikas et al., 2006; Tao et al., 2017).

In the semiarid region of the northern Great Plains, USA, traditional cropping systems that include conventional tillage with spring wheat (*Triticum aestivum* L.)–fallow have not only degraded soil quality by increasing soil erosion and reducing organic matter, but also decreased annualized yield (Lenssen et al., 2007; Sainju et al., 2013b). To replace fallow and enhance cropping intensification, pea has been increasingly grown in these regions in rotation with cereals (Miller et al., 2003a; Lenssen et al., 2007; Sainju et al., 2013). The rotation not only increased crop yields, but also reduced the risk of crop failure, enhanced biodiversity, and increased farm income (Zentner et al., 2002; Miller et al., 2015). As a result, since 1970, the pea area has steadily increased, whereas fallow area decreased (Tanaka et al., 2010; Miller et al., 2015).

© 2019 The Author(s). This is an open access article distributed under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

In addition to other crop production benefits, pea improves soil and environmental quality (Stevenson and van Kessel, 1996). Pea residue increases N supply due to higher N concentration from N fixation or lower C/N ratio than non-legumes, which increases N mineralization, thereby reducing N fertilization rates, and enhances soil water availability to succeeding crops due to its lower water requirement than nonlegume crops (Stevenson and van Kessel, 1996; Miller et al., 2003b). Pea reduces the weed, pest, and disease pressure; increases P, K, and S availability due to their greater concentrations than other crops; improves soil structure (Stevenson and van Kessel, 1996); and mitigates greenhouse gas emissions (Lupwayi and Kennedy, 2007; Sainju et al., 2014a, 2014b) compared with continuous non-legume crops.

Recommendations of improved crop cultivars in a region are usually based on their growth performance and yields over a wide range of soil and climatic conditions. These processes often fail to account for management practices that may enhance crop production. With limited global land resources, food production must be increased by twice as much to meet the demand of 9 billion people by 2050 (Hatfield and Walthall, 2015). This can be achieved by including management practices during the recommendation of crop cultivars, called the genetics × environment × management interaction, which accounts for the efficient utilization of soil water and nutrients and reduces weed and pest infections, thereby increasing crop yields (Hatfield and Walthall, 2015). The process will also result in resilient and sustainable production of crops in a changing climate.

Information on the effect of crop rotation, especially stacked vs. alternate-year rotation, on pea yield and quality is lacking. Lafond

et al. (2011) reported that crop rotation had no effect on pea stand count, but pea yield was greater with spring wheat–pea and spring wheat–spring wheat–pea rotations than continuous pea. Infestations of weeds, diseases, and pests can be reduced with stacked crop rotations where the same crop is grown successively for a number of years in rotation with other crops, thereby enhancing crop yields compared with alternate-year rotations (Garrison et al., 2014; Nickel, 2014). Weeds compete with each other in a similar environment for a longer time in these rotations and residual herbicides can be used in the first year for effective control of weeds (Garrison et al., 2014).

Crop yields can be enhanced by altering cultural practices, such as using no-tillage, banded N fertilization, and increasing seeding rate and stubble height (Lenssen et al., 2014, 2015, 2018). Pea yield can be greater with no-tillage than conventional tillage due to increased pod number by enhancing soil water storage, especially during dry periods (Lafond et al., 2006; Ruisi et al., 2012). Competition between crops and weeds can be increased with increased seeding rate, nutrient availability to weeds can be limited using banded compared to broadcast fertilization, and soil water storage can be increased and light penetration into the ground decreased using tall stubble, thereby reducing weed germination (Entz et al., 2002; Strydhorst et al., 2008; Nichols et al., 2015). Pea stand count and grain yield increased with increased seeding rate (Towendy-Smith and Wright, 1994; Nleya and Rickertsen, 2011). Similarly, pea stand count, vine length, and grain yield increased with taller wheat stubble by enhancing soil water storage due to trapping of more snow, limiting light penetration, and reducing weed growth (Huggins and Pan, 1991; Cutforth et al., 2002).

| | | | | | | | | | | | | | | | | | |
|-------------|--------|--------|-------|-------|--------|--------|-------|--------|--------|--------|--------|--------|-------|-------|-------|-------|-------|
| Improved | 101 | 102 | 103 | 104 | 105 | 106 | 107 | 108 | 109 | 110 | 111 | 112 | 113 | 114 | 115 | 116 | 117 |
| | dddd | dcDp | dedP | Dedp | dCdP | ddCp | ddeP | Ddep | dDep | dfDp | dfdP | Dfdp | dFdP | ddFp | ddfP | Ddfp | dDfP |
| Traditional | durum | durum | pea | durum | canola | canola | pea | durum | durum | durum | pea | durum | flax | flax | pea | durum | durum |
| | | | | | | | | Rep. 1 | | | | | | | | | |
| Improved | 201 | 202 | 203 | 204 | 205 | 206 | 207 | 208 | 209 | 210 | 211 | 212 | 213 | 214 | 215 | 216 | 217 |
| | dddd | dcDp | dedP | Dedp | dCdP | ddCp | ddeP | Ddep | dDep | dfDp | dfdP | Dfdp | dFdP | ddFp | ddfP | Ddfp | dDfP |
| Traditional | durum | durum | pea | durum | canola | canola | pea | durum | durum | durum | pea | durum | flax | flax | pea | durum | durum |
| | | | | | | | | | | | | | | | | | |
| Improved | 301 | 302 | 303 | 304 | 305 | 306 | 307 | 308 | 309 | 310 | 311 | 312 | 313 | 314 | 315 | 316 | 317 |
| | dfdP | Ddep | dDfP | Dedp | dfDp | ddfP | dcDp | dCdP | Ddfp | ddCp | dddd | dFdP | ddeP | ddFp | dDep | Dfdp | dedP |
| Traditional | pea | durum | durum | durum | durum | pea | durum | canola | durum | canola | durum | flax | pea | flax | durum | durum | pea |
| | | | | | | | | Rep. 2 | | | | | | | | | |
| Improved | 401 | 402 | 403 | 404 | 405 | 406 | 407 | 408 | 409 | 410 | 411 | 412 | 413 | 414 | 415 | 416 | 417 |
| | dFdP | ddCp | dDfP | ddfP | Dcdp | Dfdp | dddd | ddP | dCdP | dDcp | Ddfp | dfDp | ddeP | dcDp | dfDp | Ddcp | dedP |
| Traditional | flax | canola | durum | flax | durum | durum | durum | pea | canola | durum | durum | durum | pea | durum | pea | durum | pea |
| | | | | | | | | | | | | | | | | | |
| Improved | 501 | 502 | 503 | 504 | 505 | 506 | 507 | 508 | 509 | 510 | 511 | 512 | 513 | 514 | 515 | 516 | 517 |
| | ddFp | dDep | Dedp | dcDp | Ddep | dcDp | Dfdp | dCdP | ddfP | dDfP | ddCp | dddd | dfDp | Ddfp | dfDp | dFdP | ddCp |
| Traditional | flax | durum | durum | durum | durum | pea | durum | canola | pea | durum | canola | durum | durum | durum | pea | flax | pea |
| | | | | | | | | Rep. 3 | | | | | | | | | |
| Improved | 601 | 602 | 603 | 604 | 605 | 606 | 607 | 608 | 609 | 610 | 611 | 612 | 613 | 614 | 615 | 616 | 617 |
| | ddCp | Dfdp | ddFp | dfDp | Dcdp | dddd | ddeP | dfdP | dDfP | dFdP | dDep | dCdP | ddfP | dcDp | Ddcp | Ddfp | dedP |
| Traditional | canola | durum | flax | durum | durum | durum | pea | pea | durum | flax | durum | canola | pea | durum | durum | durum | pea |
| | | | | | | | | | | | | | | | | | |

Fig. 1. Plot plan with cultural practice (traditional and improved) as the main plot and crop rotation as the split plot treatment arranged in randomized block design with three replications. Crop rotations are dCdP, durum–canola–durum–pea; ddCp, durum–durum–canola–pea; dddd, continuous durum; ddFp, durum–durum–flax–pea; and Dfdp, durum–flax–durum–pea. See Table 1 for description of cultural practices.

Improved management techniques are needed to enhance dryland pea growth and yield (Lafond et al., 2011; Nleya and Rickertsen, 2011). We examined the effect of crop rotations [durum–durum–canola–pea (DDCP), durum–durum–flax–pea (DDFP), durum–canola–durum–pea (DCDP), and durum–flax–durum–pea (DFDP)] and cultural practices (traditional and improved) on dryland pea growth, yield, and quality from 2006 to 2011 in the semiarid region of the northern Great Plains, USA. The objectives of this study were to: (i) evaluate how crop rotations and cultural practices affect pea growth, seed characteristics, grain and biomass yields, protein concentration, and N uptake in dryland cropping systems; and (ii) determine improved management strategies that enhance pea production and quality. We hypothesized that stacked crop rotation with the improved cultural practice would enhance pea growth, yield, and quality compared with alternate-year rotation with the traditional practice.

MATERIALS AND METHODS

Site and Treatment Description

The experiment was performed from 2005 to 2011 in a dryland farm site, 11 km north of Culbertson, MT, USA. The soil at the site was a Williams loam (fine-loamy, mixed, superactive, frigid Typic Argiustoll) with 660 g kg⁻¹ sand, 180 g kg⁻¹ silt, 160 g kg⁻¹ clay, 10.1 g kg⁻¹ soil organic C, 7.2 pH, and 1.27 Mg m⁻³ bulk density at the 0- to 15-cm depth in April 2005. The site had mean monthly air temperature (115-yr avg.) from -8°C in January to 23°C in July and August, and a mean annual precipitation of 341 mm, 80% of which occurs during the growing season (April–September). The cropping history for the previous 12 yr was continuous durum under conventional tillage.

Treatments were 4-yr crop rotations of two stacked and two alternate-year rotations and two cultural practices (traditional and improved). Stacked rotations included DDCP and DDFP and alternate-year rotations included DCDP and DFDP. In all crop rotations, each phase of the rotation was present in every year and the sequence of the crop followed the order as shown in the rotation (Fig. 1). Crop rotation also included a continuous durum as another treatment for comparison, but the treatment was excluded in this study due to lack of pea in the rotation. Crops in all rotations were grown under two cultural practices (traditional and improved practices), which consisted of different combinations of tillage practices, seeding rates, N fertilization rates and methods, and durum stubble heights at crop harvest (Table 1). For instance, the traditional practice for pea included conventional tillage, seeding rate of 101 kg ha⁻¹, broadcast N fertilization, and durum stubble height of 19 cm (imposed using

plot combine), whereas the improved practice contained no-tillage, seeding rate of 140 kg ha⁻¹, banded N fertilization, and durum stubble height of 33 cm. In the traditional practice, plots were tilled in the spring before crop planting using a field cultivator to a depth of 7 to 8 cm for seedbed preparation and weed control. In the improved practice, plots were left undisturbed, except during planting and fertilization with a no-till drill in rows. The experimental design included cultural practice as the main-plot and crop rotation as the split-plot treatment arranged in a randomized complete block design with three replications (Fig. 1). The size of the main plot was 12 × 204 m and split plot 12 × 12 m.

Crop Management

Using a no-till drill equipped with low-disturbance Barton double-shoot disk openers on 20-cm centers, pea and canola were planted in early to mid-April, durum in late April, and flax in late April to early May in each year from 2005 to 2011. At planting, pea received 6 kg N ha⁻¹ and 29 kg P ha⁻¹ from monoammonium phosphate (11% N, 23% P) and 27 kg K ha⁻¹ from muriate of potash (52% K). The rates of N, P, and K applied to durum, canola, and flax from these fertilizer sources and urea (46% N) are shown in Table 1. To avoid excessive application of N fertilizers, recommended N rates for each crop were adjusted for residual soil N, which was determined as soil NO₃-N content to a depth of 60 cm measured in the autumn of the previous year. Nitrogen fertilizers were broadcast and incorporated to a depth of 8 cm into the soil due to tillage in the traditional cultural practice and were banded to a depth of 5 cm below and 5 cm to the side of the seed in the improved practice. Crops were grown in the rainfed condition.

A preplant application of glyphosate (*N*-[phosphonomethyl] glycine) at 3.36 kg ha⁻¹ a.i. was applied to all plots to control early emerging weeds. For pea, weeds were controlled by using fall-applied ethalfluralin (*N*-ethyl-*N*-[2-methyl-2-prepenyl]-2, 6-dinitro-4-trifluoromethyl[benzenamine]) at 0.12 kg ha⁻¹ a.i. and post-emergence applications of formulated, tank-mixed bentazon (3-isopropyl-1*H*-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxide) and sethoxydim (2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one) at 1.68 kg a.i. ha⁻¹ prior to crop flowering. At postharvest, residual weeds were controlled with tank-mixed glyphosate (3.36 kg a.i. ha⁻¹) and dicamba (3, 6-dichloro-2-methoxybenzoic acid) at 0.28 kg a.i. ha⁻¹. For durum, canola, and flax, in-crop weeds were controlled by applying herbicides as described by Lenssen et al. (2014, 2015).

Stand count of pea was determined at the one- to two-leaf stage by counting plants in four 1-m rows in each plot. Plant height

Table 1. Description of cultural practices (traditional and improved) used for crops in the rotation.

| Crop | Cultural practice | Tillage | Seed rate kg ha ⁻¹ | N fertilization rate kg N ha ⁻¹ | Method of N fertilization | P fertilization rate kg P ha ⁻¹ | K fertilization rate kg K ha ⁻¹ | Stubble height cm |
|--------|-------------------|-------------------|----------------------------------|--|------------------------------|--|--|-------------------------|
| | | | | | | | | |
| Durum | Traditional | Conventional till | 1,008,000† | 127 | Broadcast | 29 | 27 | 19 |
| | Improved | No-till | 1,344,000† | 127 | Banded | 29 | 27 | 33 |
| Pea | Traditional | Conventional till | 101 | 6 | Broadcast | 29 | 27 | 5 |
| | Improved | No-till | 140 | 6 | Banded | 29 | 27 | 5 |
| Canola | Traditional | Conventional till | 6 | 94 | Broadcast | 29 | 27 | 19 |
| | Improved | No-till | 9 | 94 | Banded | 29 | 27 | 19 |
| Flax | Traditional | Conventional till | 34 | 58 | Broadcast | 29 | 27 | 13 |
| | Improved | No-till | 50 | 58 | Banded | 29 | 27 | 13 |

† Number of seeds ha⁻¹.

was determined on 10 plants per plot shortly before harvest. At pea maturity in late July and early August of each year, yield component samples were measured from a 1-m segment within the plot. All pods were picked by hand, placed in a paper bag, and shelled by hand. Seeds were dried in the oven at 55°C, weighed, and counted. Two days before harvest, total aboveground biomass (leaves + stems + grains) was determined by hand clipping two 0.5-m² quadrats per plot. Pea biomass was separated from weeds, dried in the oven at 55°C for 3 d, and weighed. Grain yield was determined by harvesting grains with a self-propelled combine from an area of 50 m². Grains were air-dried, cleaned, and weighed. A sample of the grain was oven-dried at 55°C for 3 d to determine dry matter yield, from which grain yield was calculated on an oven-dried basis. Harvest index was calculated by dividing grain yield by total aboveground biomass. After measuring grain yield, the rest of the grain from each plot was harvested with a self-propelled combine and crop residue was returned to the soil. Other crops were also harvested from August (durum and canola) to September (flax) as above using the combine.

A portion of pea biomass and grain samples was ground to 1 mm for determination of N concentration (g N kg⁻¹) using the high combustion C and N analyzer (LECO, St. Joseph, MI). Nitrogen uptake (kg N ha⁻¹) in each component was determined by multiplying biomass or grain yield by N concentration. Protein concentration in pea grain was determined by multiplying N concentration by 6.25. Nitrogen harvest index was calculated by dividing grain N uptake by total biomass (grain + biomass) N uptake.

Data Analysis

Data for pea growth, seed characteristics, yield, and N uptake were analyzed using the MIXED procedure of SAS (Littell et al., 2006). Cultural practice was considered as the main-plot treatment and crop rotation as the split-plot treatment for data analysis. Fixed effects were cultural practice, crop rotation, year, and their interactions. Random effects were replication and replication × cultural practice. The data for harvest index were transformed to square root values for variance normalization before analysis and re-transformed back for presentation of the result. Means were separated using the least square means test (Littell et al., 2006) when treatments and interactions were significant. Differences among treatments and interactions were

considered significant at $P \leq 0.05$. Data from 2005 were not included in the analysis as it was considered a crop establishment year.

RESULTS AND DISCUSSION

Climate

Monthly average air temperature at the experimental site from July to August was greater in 2006 and 2007 than the 115-yr average (Table 2). In contrast, average air temperature from May to August was lower from 2008 to 2011 than the 115-yr average. Monthly total precipitation varied more than air temperature. Notable precipitation occurred in May 2007, 2010, and 2011 and July and August 2009 and 2010 that were greater than the 115-yr average. In contrast, below-average precipitation occurred from June to August 2007 and 2008. Growing season precipitation (April–September) accounted for 81% of the total annual precipitation and was lower in 2007 and 2008 than other years and the 115-yr average.

Pea Stand Count and Height

Pea stand count varied with cultural practices and years, with significant interaction for cultural practice × year (Table 3). Averaged across crop rotations, stand count was greater in the traditional than the improved cultural practice in 2006, but the trend reversed from 2008 to 2011 (Table 4). Averaged across crop rotations and years, stand count was 29% greater with the improved than the traditional practice (Table 5). Averaged across treatments, stand count was greater in 2009 than other years, except 2011. Crop rotation had no effect on stand count.

The greater pea stand count with the traditional cultural practice in 2006 was probably a result of near or above-average air temperature and precipitation in April and May (Table 2) when seeds germinate. It is likely that increased precipitation and air temperature in April 2006 enhanced seed germination and therefore stand count in the traditional practice (DeFelice et al., 2006; West et al., 1996). In the improved practice, increased crop residue accumulated at the soil surface due to improved cultural practice, likely the no-tillage practice, and reduced light penetration due to taller durum stubble may have reduced soil temperature during the period with above-average precipitation, which probably reduced stand count with

Table 2. Monthly average air temperature and total precipitation from 2006 to 2011 at the experimental site.

| Month | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 115-yr avg. |
|--------------------------|------|------|------|------|------|------|-------------|
| <u>Air temp., °C</u> | | | | | | | |
| April | 8.9 | 5.6 | 4.9 | 4.8 | 7.2 | 3.6 | 7.5 |
| May | 13.7 | 13.0 | 11.6 | 11.1 | 9.8 | 10.1 | 13.4 |
| June | 18.2 | 18.6 | 15.4 | 15.8 | 16.6 | 15.8 | 18.2 |
| July | 24.1 | 24.7 | 21.0 | 17.7 | 19.1 | 20.8 | 21.8 |
| August | 21.3 | 20.3 | 20.6 | 17.7 | 18.7 | 19.8 | 21.2 |
| September | 12.0 | 11.8 | 12.7 | 16.7 | 12.0 | 14.5 | 14.7 |
| <u>Total precip., mm</u> | | | | | | | |
| April | 80 | 21 | 12 | 53 | 33 | 35 | 22 |
| May | 44 | 128 | 43 | 24 | 118 | 172 | 51 |
| June | 55 | 49 | 58 | 27 | 69 | 71 | 71 |
| July | 30 | 21 | 29 | 100 | 125 | 42 | 68 |
| August | 36 | 8 | 21 | 96 | 83 | 25 | 34 |
| September | 67 | 19 | 62 | 23 | 23 | 17 | 29 |
| April–September | 311 | 245 | 225 | 323 | 451 | 362 | 275 |
| January–December | 339 | 283 | 336 | 406 | 522 | 397 | 341 |

Table 3. Analysis of variance for pea growth, yield, and N uptake with crop rotation (R), cultural practice (C), and year (Y) as sources of variance.

| Source | Stand count | Pod no. | Plant height | Seed no. | Seed wt. | Grain yield | Biomass yield | Harvest index | Grain N uptake | Biomass N uptake | N harvest index | Grain protein conc. |
|-----------|------------------------|---------------------|--------------|------------------------|-----------------------|---------------------|---------------------|---------------------|-----------------------|-----------------------|-------------------------|---------------------|
| | plants m ⁻² | pod m ⁻² | cm | seed pod ⁻¹ | mg seed ⁻¹ | kg ha ⁻¹ | kg ha ⁻¹ | kg kg ⁻¹ | kg N ha ⁻¹ | kg N ha ⁻¹ | kg N kg ⁻¹ N | g kg ⁻¹ |
| R | NS† | * | * | NS | NS | *** | NS | NS | *** | NS | NS | NS |
| C | ** | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| R × C | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| Y | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| R × Y | NS | NS | NS | NS | NS | NS | * | NS | * | ** | NS | ** |
| C × Y | *** | * | NS | NS | NS | NS | NS | NS | NS | * | NS | ** |
| R × C × Y | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |

*Significant at $P \leq 0.05$.

**Significant at $P \leq 0.01$.

***Significant at $P \leq 0.001$.

† NS, not significant.

Table 4. Interaction between cultural practice and year on pea stand count, pod number, biomass N uptake, and grain protein concentration.

| Cultural practice† | Year | | | | | |
|--------------------|---|------|------|------|------|------|
| | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
| | <u>Stand count, plants m⁻²</u> | | | | | |
| Traditional | 78a‡ | 52 | 64b | 64b | 63b | 57b |
| Improved | 66b | 65 | 79a | 94a | 85a | 97a |
| | <u>Pod no., pod m⁻²</u> | | | | | |
| Traditional | 220 | 326 | 331a | 249 | 271b | 278 |
| Improved | 201 | 356 | 289b | 260 | 345a | 298 |
| | <u>Biomass N uptake, kg N ha⁻¹</u> | | | | | |
| Traditional | 84a | 59b | 92 | 68 | 77 | 50 |
| Improved | 70b | 77a | 79 | 71 | 85 | 61 |
| | <u>Grain protein conc., g kg⁻¹</u> | | | | | |
| Traditional | 274a | 246a | 279 | 282b | 285 | 251 |
| Improved | 264b | 240b | 277 | 290a | 284 | 252 |

† See Table 1 for the description of the cultural practice.

‡ Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.

Table 5. Pea growth, yield, and N uptake as affected by crop rotation, cultural practice, and year.

| Treatment | Stand count | Pod no. | Plant height | Seed no. | Seed wt. | Grain yield | Biomass yield | Harvest index | Grain N uptake | Biomass N uptake | N harvest index | Grain protein conc. |
|---------------------------|------------------------|---------------------|--------------|------------------------|-----------------------|---------------------|---------------------|---------------------|-----------------------|-----------------------|-------------------------|---------------------|
| | plants m ⁻² | pod m ⁻² | cm | seed pod ⁻¹ | mg seed ⁻¹ | kg ha ⁻¹ | kg ha ⁻¹ | kg kg ⁻¹ | kg N ha ⁻¹ | kg N ha ⁻¹ | kg N kg ⁻¹ N | g kg ⁻¹ |
| <u>Crop rotation†</u> | | | | | | | | | | | | |
| DNDP | 73 | 304a‡ | 48a | 4.0 | 210 | 2002a | 3536 | 0.38 | 86a | 75 | 0.54 | 268 |
| DNDP | 72 | 267b | 45b | 3.7 | 208 | 1707b | 3348 | 0.36 | 73b | 69 | 0.51 | 268 |
| DFDP | 73 | 297ab | 49a | 3.8 | 205 | 1982a | 3511 | 0.34 | 85a | 71 | 0.54 | 270 |
| DDFP | 71 | 273b | 47ab | 3.8 | 208 | 1729b | 3488 | 0.38 | 74b | 75 | 0.51 | 268 |
| <u>Cultural practice§</u> | | | | | | | | | | | | |
| Traditional | 63b | 279 | 48 | 3.9 | 210 | 1956 | 3474 | 0.37 | 76 | 74 | 0.51 | 270 |
| Improved | 81a | 292 | 47 | 3.8 | 205 | 1955 | 3468 | 0.35 | 83 | 72 | 0.53 | 268 |
| <u>Year</u> | | | | | | | | | | | | |
| 2006 | 72b | 211d | 44d | 4.0b | 179c | 1363d | 3057b | 0.29c | 58e | 77ab | 0.43b | 269c |
| 2007 | 58c | 341a | 58a | 4.4a | 203b | 2324a | 4256a | 0.39b | 90ab | 68b | 0.58a | 243e |
| 2008 | 72b | 310a | 46cd | 3.3d | 199b | 1630c | 3453b | 0.32c | 72d | 86a | 0.46b | 278b |
| 2009 | 81a | 255c | 33c | 3.6c | 253a | 1816b | 3183b | 0.37b | 83bc | 69b | 0.55a | 286a |
| 2010 | 74b | 308ab | 52b | 3.8bc | 204b | 2146a | 3126b | 0.44a | 97a | 81a | 0.55a | 284a |
| 2011 | 77ab | 288b | 49bc | 4.0b | 209b | 1851b | 3299b | 0.38b | 75c | 56c | 0.58a | 252d |

† Crop rotations are DNDP, durum–canola–durum–pea; DNDP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea, and DFDP, durum–flax–durum–pea.

‡ Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.

§ See Table 1 for the description of the cultural practice.

the improved practice in 2006. Several researchers (DeFelice et al., 2006; West et al., 1996) have found that crop stand count was lower for no-tillage than conventional tillage due to lower soil temperature. In contrast, increased soil water conservation due to improved practice with no-tillage and taller stubble height, followed by higher seed rate may have increased stand count from 2008 to 2011.

Increased pea stand count due to higher seed rate as a result of reduced weed growth was reported by some researchers (Towendy-Smith and Wright, 1994; Nleya and Rickertsen, 2011). Similarly, increased pea stand due to taller stubble height as a result of increased soil water content has been observed by others (Aase and Siddoway, 1980; Huggins and Pan, 1991; Lenssen et al., 2018). Various researchers (Lafond et al., 2011; Nleya and Rickertsen, 2011) have reported that crop rotation did not affect pea stand count. Greater stand count in 2009 than other years was probably due to favorable air temperature and precipitation in April and May (Table 2).

Pea plant height varied with crop rotations and years, but cultural practice had no effect on plant height (Table 3). Averaged across cultural practices and years, pea was 3 to 4 cm taller with DCDP and DFDP than DDCP (Table 5). Averaged across treatments, pea was 6 to 25 cm taller in 2007 than other years.

Our results are in agreement with those reported by Nleya and Rickertson (2011), who found that seeding rate had no effect on pea height, but in contrast to those shown by Towendy-Smith and Wright (1994), who observed that seeding rate had variable effect on pea height in various years in western Canada. Our results indicate that alternate-year crop rotation increased pea height compared with stacked rotation, particularly with DDCP. Although data are not shown, preplant soil water content measured to a depth of 2 m before pea planting in April was significantly greater with DCDP (10–46 mm) and DFDP (144–149 mm) than DDCP and DDFP (103–134 mm). Similarly, postharvest soil water content after pea harvest in August was significantly greater with DCDP (14–47 mm) and DFDP (100–104 mm) than DDCP and DDFP (57–86 mm). It is likely that increased soil water content enhanced pea growth and therefore increased plant height with DCDP compared with DDCP. Increased precipitation and favorable air temperature in May probably increased pea height in 2007 compared with other years. Shorter pea height closer to the ground poses challenges for harvesting grain using combine (Towendy-Smith and Wright, 1994).

Pea Pod Number, Seed Number, and Seed Weight

Pea pod number varied with crop rotations and years, with a significant interaction for cultural practice \times year (Table 3). Averaged across crop rotations, pod number was greater for the traditional than the improved cultural practice in 2008, but the trend reversed in 2010 (Table 4). Averaged across cultural practices and years, pod number was greater with DCDP than DDCP and DDFP (Table 5). Averaged across treatments, pod number was greater in 2007 and 2008 than other years, except 2010.

Traditional cultural practice led to increased pod number under dry condition in 2008 when the growing season precipitation (April–September) was lower than other years and the 115-yr average (Table 2). The opposite was true with the improved practice in 2010 when the growing season precipitation was higher than other years. It appears that soil water availability affected pea pod number. The traditional practice favored greater pod number, probably due to reduced seed number under limited water availability in the dry year, but the reverse was true with the improved practice in the wet

year. Our results contradicted those reported by several researchers (Towendy-Smith and Wright, 1994; Nleya and Rickertsen, 2011), who found that that increased seeding rate decreased pea pod number. As with plant height, increased pod number with DCDP and DFDP suggests that alternate-year rotation enhanced pea pod number, a fact probably related to soil water content. Similarly, greater pod number in 2007 than other years was probably related to favorable air temperature and growing season precipitation.

Seed number and weight varied with years, but were not significant for treatments and their interactions (Table 3). Several researchers (Lafond et al., 2011; Ruisi et al., 2012) found that crop rotation or tillage did not affect pea seed weight, but others (Nleya and Rickertsen, 2011) observed greater seed number pod^{-1} with increased seeding rate. Averaged across treatments, seed number was greater in 2007 and seed weight greater in 2009 than other years (Table 5). Increased pod number probably increased seed number, but reduced seed weight in 2007.

Pea Biomass and Grain Yields and Harvest Index

Pea biomass yield varied with years, with a significant crop rotation \times year interaction (Table 3). Averaged across cultural practices, biomass was greater with DCDP than DDCP and DDFP in 2008 (Table 6). In 2011, biomass was greater with DFDP and DDFP than DDCP. Averaged across treatments, biomass was greater in 2007 than other years (Table 5).

Alternate-year crop rotation appeared to increase pea biomass yield compared with stacked rotation, regardless of growing season precipitation, as biomass was greater with DCDP in 2008 when the growing season precipitation was lower and greater with DFDP in 2011 when the growing season precipitation was greater than other years (Table 2). This was probably due to increased plant height (Table 5) and likely associated with reduced infections of weeds, diseases, and pests with alternate-year rotation compared with stacked rotation. It appeared that durum provided a more favorable environment for increasing biomass yield of succeeding pea in alternate-year rotation compared with canola or flax in stacked rotation. Our results are in contrast to those reported by several researchers (Garrison et al., 2014; Nickel, 2014), who found that reduced infestation of pests increased crop yields with stacked compared with alternate-year crop rotation. Although lack of crop rotation can increase disease incidence and severity, thereby compromising pea yield (Cousin, 1997), we observed that disease symptoms on pea were rare in this study and always limited to only single, isolated plants. An exception, however, occurred for increased biomass with DDFP in 2011 when the increased growing season precipitation favored pea growth and biomass. In this year, greater biomass with DDFP than DDCP showed that pea biomass increased following flax compared with following canola, probably due to greater soil water availability. In 2010, we observed that biomass of flax in DDFP (3195 kg ha^{-1}) was lower than that of canola in DDCP (4814 kg ha^{-1}), which may have resulted in higher available soil water for pea following flax than following canola in 2011. Pea yield was enhanced with increased available soil water and during years with above-average precipitation (Payne et al., 2000, 2001). As noted above, increased biomass in 2007 than other years was due to enhanced plant height (Table 5).

Pea grain yield varied with crop rotations and years (Table 3). Averaged across cultural practices and years, grain yield was greater with DCDP and DFDP than other crop rotations (Table 5).

Table 6. Interaction between crop rotation and year on pea biomass yield, grain and biomass N uptake, and grain protein concentration.

| Crop rotation† | Year | | | | | |
|----------------|---|-------|--------|-------|-------|--------|
| | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
| | <u>Biomass yield, kg ha⁻¹</u> | | | | | |
| DCDP | 3459 | 4232 | 4223a‡ | 3109 | 3240 | 2949ab |
| DDCP | 3611 | 4669 | 2764b | 3176 | 3149 | 2720b |
| DFDP | 3419 | 4081 | 3848ab | 3108 | 2734 | 3735a |
| DDFP | 3541 | 3541 | 2976b | 3340 | 3382 | 3790a |
| | <u>Biomass N uptake, kg N ha⁻¹</u> | | | | | |
| DCDP | 79 | 65 | 110a | 67 | 84 | 47b |
| DDCP | 77 | 76 | 68b | 70 | 82 | 42b |
| DFDP | 79 | 64 | 103a | 69 | 72 | 65ab |
| DDFP | 72 | 66 | 62b | 72 | 85 | 69a |
| | <u>Grain N uptake, kg N ha⁻¹</u> | | | | | |
| DCDP | 65 | 88 | 87a | 84 | 110a | 80 |
| DDCP | 55 | 85 | 58b | 77 | 89b | 73 |
| DFDP | 62 | 97 | 92a | 82 | 100ab | 78 |
| DDFP | 51 | 92 | 52b | 86 | 92ab | 67 |
| | <u>Grain protein conc., g kg⁻¹</u> | | | | | |
| DCDP | 272ab | 235b | 285a | 282b | 285 | 253 |
| DDCP | 265b | 250a | 269b | 291a | 285 | 249 |
| DFDP | 273a | 243ab | 283a | 287ab | 284 | 252 |
| DDFP | 266ab | 247ab | 274b | 284ab | 284 | 252 |

† Crop rotations are DCDP, durum–canola–durum–pea; DDCP, durum–durum–canola–pea; DDFP, durum–durum–flax–pea, and DFDP, durum–flax–durum–pea.

‡ Numbers followed by different letters within a column in a set are significantly different at $P = 0.05$ by the least square means test.

Averaged across treatments, grain yield was greater in 2007 and 2010 than other years. Increased grain yield with DCDP and DFDP was probably a result of increased pod number and suggests that alternate-year rotation favored grain yield compared with stacked rotation, a case similar to that observed for biomass yield. Similarly, increased grain yield in 2007 and 2010 was probably due to increased pod and seed numbers during those years.

Harvest index for pea varied with years, but was not significant for treatments and interactions (Table 3). Several researchers (Towendy-Smith and Wright, 1994; Nleya and Rickertsen, 2011) have reported that seeding rate had no effect on pea harvest index in the northern Great Plains and western Canada. Averaged across treatments, harvest index was greater in 2010 when the growing season precipitation was greater than other years (Table 5). Greater grain than total biomass yield increased harvest index in that year.

Pea Biomass and Grain Nitrogen Uptake, Grain Protein Concentration, and Nitrogen Harvest Index

Pea biomass N uptake varied with years, with significant interactions for crop rotation \times year and cultural practice \times year (Table 3). Averaged across crop rotations, biomass N uptake was greater with the traditional than the improved cultural practice in 2006, but the trend reversed in 2007 (Table 4). Averaged across cultural practices, biomass N uptake was greater with DCDP and DFDP than other crop rotations in 2008, but was greater with DDFP than DCDP and DDCP in 2011 (Table 6). Averaged across treatments, biomass N uptake was greater in 2008 and 2010 than other years, except 2006 (Table 5).

Increased N fixation due to greater stand count (Table 4) during favorable air temperature and above-average growing season precipitation probably increased biomass N uptake with the traditional cultural practice in 2006. The opposite was true with the

improved practice in 2007 when the growing season precipitation was lower. Although not significant, greater stand count, due to enhanced soil water conservation with no-tillage and taller durum stubble height and increased seed rate, may have increased pea growth and therefore biomass N uptake with the improved cultural practice in 2007. Increased biomass N uptake with DCDP and DFDP in 2008 and DDFP in 2011, however, was due to greater biomass yield (Table 6). Our results indicate that alternate-year crop rotation increased biomass N uptake compared with stacked rotation during dry year in 2008, but increased with stacked rotation of durum with flax and pea during the year with normal precipitation in 2011.

Protein concentration in pea grain varied with years, with significant interactions for crop rotation \times year and cultural practice \times year (Table 3). Averaged across crop rotations, protein concentration was greater with the traditional than the improved cultural practice in 2006 and 2007, but the trend reversed in 2009 (Table 4). Averaged across cultural practices, protein concentration was greater with DFDP than DDCP in 2006, but was greater with DDCP than DCDP in 2007 and 2009 (Table 6). In 2008, protein concentration was greater with DCDP and DFDP than other crop rotations. Averaged across treatments, protein concentration was greater in 2009 and 2010 than other years (Table 5).

Although grain protein concentration varied with crop rotations in various years, alternate-year rotation had greater protein concentration than stacked rotation during the dry year in 2008 with below-average precipitation, a case similar to that observed for pea biomass yield and N uptake. It is likely that pea N fixation improved with alternate-year rotation during dry year, thereby increasing protein concentration. In years with near or above-average precipitation, both stacked and alternate-year rotations had greater protein concentration, probably due to increased soil N availability from mineralization of soil organic matter. In these years, protein concentration increased following canola than following durum.

It has been known that legumes fix about 70% of N from the atmosphere and take 30% from the soil (Meisinger and Randall, 1991; Ross et al., 2008). Enhanced N fixation also may have increased protein concentration with the traditional cultural practice in 2006 and 2007 when the growing season precipitation was near or below the 115-yr average (Table 2). Above-average precipitation in 2009 and 2010 resulted in increased protein concentration (285 vs. 278 g kg⁻¹ or less, Table 5), regardless of treatments, probably due to enhanced pea growth, N fixation, and N absorption from the soil.

Pea grain N uptake varied with crop rotations and years, with a significant crop rotation × year interaction (Table 3). Averaged across cultural practices, grain N uptake was greater with DCDP and DFDP than other crop rotations in 2008 and greater with DCDP than DDCP in 2010 (Table 6). Averaged across cultural practices and years, grain N uptake was greater with DCDP and DFDP than other rotations. Averaged across treatments, grain N uptake was greater in 2010 than other years, except 2007 (Table 5).

Greater grain N uptake with DCDP and DFDP was due to increased grain yield and protein concentration and indicates that alternate-year rotation also favored grain N uptake compared with stacked rotation. Reduced pest incidences following durum in the alternate-year rotation compared with following canola and flax in the stacked rotation likely increased pod number, plant height, and grain yield, thereby enhancing grain N uptake with alternate-year rotation. Similarly, increased grain yield and protein concentration may have increased grain N uptake in 2010 when the growing season precipitation was higher than other years (Table 2).

Nitrogen harvest index was not significant for treatments and interactions, but varied with years (Table 3). Averaged across treatments, N harvest index was greater in 2007, 2009, 2010, and 2011 than other years (Table 5). Greater grain N uptake than total biomass (grain + biomass) N uptake increased N harvest index in these years.

Implication of Management Strategies

Results of this study suggest that alternate-year crop rotation enhanced pea pod number, plant height, grain yield, and N uptake compared with stacked rotation and the improved cultural practice that included no-tillage system, increased seeding rate and durum stubble height, and banded N fertilization increased stand count compared with the traditional practice. Reduced pest incidence due to alternate-year rotation and increased seeding rate, enhanced soil water conservation due to no-tillage system and increased durum stubble height, and to some extent, efficient N use with banded N fertilization may have favored pea production and quality with these management strategies. No-tillage can save energy by not using the tillage equipment and also can enhance soil and environmental quality compared with conventional tillage by improving soil structure, maintaining organic matter, increasing water infiltration and storage, reducing erosion, and mitigating greenhouse gas emissions (Ruisi et al., 2012; Sainju et al., 2013, 2014a). Although additional use of herbicides to manage weeds in the no-tillage system and increased seeding rate can increase the cost of pea production in the improved cultural practice, economic analysis is required to examine if benefits from increased pea production and enhanced soil and environmental quality using improved management strategies outweigh the cost of cultivation.

CONCLUSIONS

Crop rotation and cultural practice had variable effect on dryland pea growth, yield, and quality in various years in the northern Great Plains, USA. In general, alternate-year rotation enhanced pea height, pod number, grain yield, and N uptake compared with stacked rotation, results that were contrary to our hypothesis. Improved cultural practice increased stand count compared with the traditional practice in dry years, but reduced pod number, biomass N content, and grain protein concentration in wet years. Seed number, seed weight, harvest index, and N harvest index varied with years. Pea growth, yield, and quality, however, responded well in years with above-average precipitation. Dryland pea growth, yield, and N uptake can be increased using alternate-year crop rotation by enhancing pod number and plant height compared with stacked rotations. Additional research using other broadleaf and small grain crops is necessary to confirm that alternate year rotations are generally superior over time for pea production under dryland cropping systems in semiarid environments.

ACKNOWLEDGMENTS

The authors gratefully acknowledge expert assistance from Bill Iversen, Joy Barsotti, René France, Mark Gaffri, and Michael Johnson in field work and laboratory analysis.

REFERENCES

- Aase, J.K., and F.H. Siddoway. 1980. Stubble height effects on seasonal microclimate, water balance, and plant development of no-till winter wheat. *Agric. For. Meteorol.* 21:1–20. doi:10.1016/0002-1571(80)90065-5
- Cousin, R. 1997. Pea (*Pisum sativum* L.). *Field Crops Res.* 53:111–130. doi:10.1016/S0378-4290(97)00026-9
- Cutforth, H.W., B.G. McConkey, D. Ulrich, P.R. Miller, and S.V. Angadi. 2002. Yield and water-use efficiency of pulses seeded directly into standing stubble in the semiarid Canadian Prairie. *Can. J. Plant Sci.* 82:681–686. doi:10.4141/P01-111
- DeFelice, M.S., P.R. Carter, and S.B. Mitchell. 2006. Influence of tillage on corn and soybean yields in the United States and Canada. *Crop Manag.* 5. doi:10.1094/CM-2006-0626-01-RS.
- Entz, M.H., V.S. Baron, P.M. Carr, D.W. Meyer, S.R. Smith, Jr., and W.P. McCaughey. 2002. Potential of forages to diversify cropping systems in the northern Great Plains. *Agron. J.* 94:240–250. doi:10.2134/agronj2002.0240
- Garrison, A.J., A.D. Miller, M.J. Ryan, S.H. Roxborough, and K. Shea. 2014. Stacked crop rotations exploit weed-weed competition for sustainable weed management. *Weed Sci.* 62:166–176. doi:10.1614/WS-D-13-00037.1
- Hatfield, J.L., and C.L. Walthall. 2015. Meeting global food needs: Realizing the potential via. *Genetics × Environment × Management interaction.* *Agron. J.* 107:1215–1226. doi:10.2134/agronj15.0076
- Hood-Niefer, S.D., T.D. Warkentin, R.N. Chibbar, A. Vandenberg, and R.T. Tyler. 2012. Effect of genotype and environment on the concentration of starch and protein in and the physico-chemical properties of starch from field pea and favabean. *J. Sci. Food Agric.* 92:141–150. doi:10.1002/jsfa.4552
- Huggins, D.R., and W.L. Pan. 1991. Wheat stubble management affects growth, survival, and yield of winter grain legumes. *Soil Sci. Soc. Am. J.* 55:823–829. doi:10.2136/sssaj1991.03615995005500030032x
- Lafond, G.P., W.E. May, C.B. Holzapfel, R.L. Lemke, and N.Z. Lupwayi. 2011. Intensification of field pea production: Impact on agronomic performance. *Agron. J.* 103:396–403. doi:10.2134/agronj2010.0309
- Lafond, G.P., W.E. May, F.C. Stevenson, and D.A. Derksen. 2006. Effect of tillage system and rotation on crop production for a thin Black Chernozem in the Canadian Prairies. *Soil Tillage Res.* 89:232–245. doi:10.1016/j.still.2005.07.014
- Lenzen, A.W., G.D. Johnson, and G.R. Carlson. 2007. Cropping sequence and tillage system influence annual crop production and water use in semiarid Montana, USA. *Field Crops Res.* 100:32–43. doi:10.1016/j.fcr.2006.05.004

- Lenssen, A.W., U.M. Sainju, B.L. Allen, and R.G. Evans. 2015. Management and tillage influence forage barley productivity and water use in a semiarid environment. *Agron. J.* 107:551–557. doi:10.2134/agronj14.0421
- Lenssen, A.W., U.M. Sainju, W.M. Iversen, B.L. Allen, and R.G. Evans. 2014. Diversification, tillage, and management influence spring wheat yield and water use. *Agron. J.* 106:1445–1454. doi:10.2134/agronj14.0119
- Lenssen, A.W., U.M. Sainju, J.D. Jabro, B.L. Allen, and W.B. Stevens. 2018. Dryland pea productivity and soil water responses to tillage, crop rotation, and weed management practice. *Agron. J.* 110:1843–1853. doi:10.2134/agronj2018.03.0182
- Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2006. SAS for mixed models. SAS Institute, Cary, NC.
- Lupwayi, N.Z., and A.C. Kennedy. 2007. Grain legumes in the northern Great Plains: Impacts on selected biological properties. *Agron. J.* 99:1700–1709. doi:10.2134/agronj2006.0313s
- Meisinger, J.J., and G.W. Randall. 1991. Estimating nitrogen budgets for soil-crop systems. In: R.L. Follett, editor, *Managing nitrogen for groundwater quality and farm profitability*. SSSA, Madison, WI. p. 85–124.
- Miller, P.R., A. Bekkerman, C.A. Jones, M.H. Burgess, J.A. Holmes, and R.E. Engel. 2015. Pea in rotation with wheat reduced uncertainty of economic returns in southwest Montana. *Agron. J.* 107:541–550. doi:10.2134/agronj14.0185
- Miller, P.R., Y. Gan, B.G. McConkey, and C.L. McDonald. 2003a. Pulse crops for the northern Great Plains: I. Grain productivity and residual effects on soil water and nitrogen. *Agron. J.* 95:972–979. doi:10.2134/agronj2003.9720
- Miller, P.R., Y. Gan, B.G. McConkey, and C.L. McDonald. 2003b. Pulse crops for the northern Great Plains: II. Cropping sequence effects on cereal, oilseed, and pulse crops. *Agron. J.* 95:980–986. doi:10.2134/agronj2003.9800
- Nichols, V., N. Verhulst, R. Cox, and B. Govaerts. 2015. Weed dynamics and conservation agriculture principles: A review. *Field Crops Res.* 183:56–68. doi:10.1016/j.fcr.2015.07.012
- Nickel, R. 2014. Stacking crop rotation controls pests. https://www.agriculture.com/crops/corn/production/stacking-crop-rotation-controls-pests_137-ar45188 (accessed 23 Feb. 2016).
- Nleya, T., and J. Rickertsen. 2011. Seeding rate and variety effect on yield, yield components, and economic returns of field pea in the northern Great Plains. *Crop Manag.* 10. doi:10.1094/CM-2011-0221-01-RS
- Payne, W.A., P.E. Rasmussen, C. Chen, and R.E. Ramig. 2000. Precipitation, temperature, and tillage effect upon productivity of a winter wheat-dry pea rotation. *Agron. J.* 92:933–937. doi:10.2134/agronj2000.925933x
- Payne, W.A., P.E. Rasmussen, C. Chen, and R.E. Ramig. 2001. Addressing simple wheat and pea models using data from a long-term tillage experiment. *Agron. J.* 93:250–260. doi:10.2134/agronj2001.931250x
- Ratnayake, W.S., R. Hoover, and T. Wakentint. 2002. Pea starch: Composition, structure, and properties: A review. *Starke* 54:217–234. doi:10.1002/1521-379X(200206)54:6<217::AID-STAR217>3.0.CO;2-R
- Ross, S.M., R.C. Izaurralde, H.H. Janzen, J.A. Robertson, and W.B. McGill. 2008. The nitrogen balance of three long-term agroecosystems on a boreal soil in western Canada. *Agric. Ecosyst. Environ.* 127:241–250. doi:10.1016/j.agee.2008.04.007
- Ruisi, P., D. Giambalvo, G.D. Miceli, A.S. Frenda, S. Saria, and G. Amato. 2012. Tillage effects on yield and nitrogen fixation of legumes in Mediterranean conditions. *Agron. J.* 104:1459–1466. doi:10.2134/agronj2012.0070
- Sainju, U.M., A.W. Lenssen, and J.L. Barsotti. 2013. Dryland malt barley yield and quality affected by tillage, cropping sequence, and nitrogen fertilization. *Agron. J.* 105:329–340. doi:10.2134/agronj2012.0343
- Sainju, U.M., W.B. Stevens, T. Caesar-Tonthat, M.A. Liebig, and J. Wang. 2014a. Net global warming potential and greenhouse gas intensity influenced by irrigation, tillage, crop rotation, and nitrogen fertilization. *J. Environ. Qual.* 43:777–788. doi:10.2134/jeq2013.10.0405
- Sainju, U.M., J. Wang, and J.L. Barsotti. 2014b. Net global warming potential and greenhouse gas intensity affected by cropping sequence and nitrogen fertilization. *Soil Sci. Soc. Am. J.* 78:248–261. doi:10.2136/sssaj2013.08.0325
- Stevenson, F.C., and C. van Kessel. 1996. The nitrogen and non-nitrogen rotational benefits of pea to succeeding crops. *Can. J. Plant Sci.* 76:735–745. doi:10.4141/cjps96-126
- Strydhorst, S.M., J.R. King, K.H. Lopetinsky, and K.N. Harker. 2008. Weed interference, pulse species, and plant density effect on rotational benefits. *Weed Sci.* 56:249–258. doi:10.1614/WS-07-118.1
- Tan, H.Z., Z.G. Li, and B. Tan. 2009. Starch noodles: History, classification, materials, processing, structure, nutrition, quality evaluating and improvement. *Food Res. Int.* 42:551–576. doi:10.1016/j.foodres.2009.02.015
- Tanaka, D.L., D.J. Lyon, P.R. Miller, S.D. Merrill, and B. McConkey. 2010. Soil and water conservation advances in the semiarid northern Great Plains. In: W.F. Schillinger, editor, *Soil and water conservation advances in the United States*. SSSA Spec. Publ. 60. SSSA, Madison, WI. p. 81–102.
- Tao, A., R. Keshavarz, J. Huang, Y.A. Mohammed, M. Espe, and C. Chen. 2017. Variation in yield, starch, and protein of dry pea grown across Montana. *Agron. J.* 109:1491–1501. doi:10.2134/agronj2016.07.0401
- Towendy-Smith, L., and A.T. Wright. 1994. Field pea cultivar and weed response to crop seed rate in western Canada. *Can. J. Plant Sci.* 74:378–393.
- Tzitzikas, E.N., J.P. Vincken, and J. DeGroot. 2006. Genetic variation in pea seed globulin composition. *J. Agric. Food Chem.* 54:425–433. doi:10.1021/jf0519008
- West, T.D., D.R. Griffith, G.C. Steinhardt, E.J. Klavivko, and S.D. Parsons. 1996. Effect of tillage and rotation on agronomic performance of corn and soybean: Twenty-years study on dark silty clay loam soil. *J. Prod. Agric.* 9:241–248. doi:10.2134/jpa1996.0241
- Zentner, R.P., D.D. Wall, C.N. Nagy, E.G. Smith, D.L. Young, P.R. Miller, C.A. Campbell, B.G. McConkey, S.A. Bratt, G.P. Lafond, A.M. Johnston, and D.A. Derksen. 2002. Economics of crop diversification and soil tillage opportunities in the Canadian Prairies. *Agron. J.* 94:216–230. doi:10.2134/agronj2002.0216