Replacing fallow with field pea in wheat production systems across western Nebraska

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

This is the peer reviewed version of the following article: [Replacing fallow with field pea in wheat production systems across western Nebraska. Agronomy Journal 114, 6 p3329-3346 (2022)], which has been published in final form at https://doi.org/10.1002/agj2.21194.

TITLE

Replacing Fallow with Field Pea in Wheat Production Systems across western Nebraska

ABSTRACT

Integration of field pea (*Pisum sativum* L.) into dryland cropping systems has increased due to ecological and economic benefits, paired with a growing market for pea-derived products. Challenges exist in the High Plains that limit the intensive integration of crop rotations with the replacement of fallow periods with field pea in wheat-based systems. This experiment compares chemical summer fallow to field pea in a fallow - wheat rotation at two locations in western Nebraska. Soil water content, soil fertility, N mineralization, field pea yield, and subsequent hard red winter wheat (HWW) yields were recorded. Subsequent HWW yields were not different between crop sequences ($P = 0.42$). The interaction of site – year with crop sequence explained the HWW yield differences ($P = 0.0005$), mostly due to precipitation variability among site-years. Most soil parameters tested only showed a main effect of date due to temporal changes in soil nutrient cycling. Replacing summer fallow with field pea resulted in reduced soil water content, however that did not result in long-term moisture deficiency due to crop sequence type. System annualized gross revenue was equal to or greater for two site-years for field pea compared to fallow, with an average increase of \$113.15 ha^{-1}. Pea – wheat reduced annualized net losses in one site – year by \$70 ha^{-1} compared to fallow – wheat in the ‘average’ pricing model. Among three site – years and three pricing models, pea-wheat resulted in greater net profit or reduced net losses compared to fallow-wheat in five site – year comparisons.

ABBREVIATIONS

1. CGP: Central Great Plains
2. CSF: Chemical Summer Fallow

3. FP: Field Pea
4. HP: High Plains
5. HWW: Hard Red Winter Wheat
6. N: Nitrogen
7. PLS: Pure Live Seed
8. PUE: Precipitation Use Efficiency
9. W-C-F: Wheat-Corn-Fallow
10. W-C-P: Wheat-Corn-Pea
11. W-F: Wheat-Fallow
12. UAN: Urea Ammonium Nitrate

CORE IDEAS

1. Soil water levels were not different between crop sequences until pod development began in pea plots.
2. Site-year and date explained soil water content variability more accurately than the crop sequence.
3. Pea did not decrease soil nutrients, although seasonal nutrient cycling was observed during the study.
4. Available soil nutrients varied among site-years and date of sampling due to nutrient cycling dynamics.
5. Replacing fallow with field pea resulted in reduced subsequent wheat yield in one of three site – years.

INTRODUCTION

Following the 2020 growing season, over 3.6 M tillable hectares in the US were managed as fallow, as reported by the Farm Service Agency (*FSA Crop Acerage Data*, 2022). Although this is a decrease from 12.5 M hectares managed as fallow during the mid-1970s across the US, many farms located within the Great Plains regions still used chemical summer fallow (CSF) regularly as a cropping system management practice to conserve soil water (Black *et al*., 1981; Dhuyvetter *et al*., 1996b; Smith & Young, 2000). While CSF can increase soil water content for the subsequent crop following fallow compared to intensive crop rotations, hard winter wheat (HWW)-fallow systems have been shown to only store 35% of all precipitation received during two years under no-till management, due to high evaporation loss during the fallow period (Anderson *et al*., 1999; D. C. Nielsen & M. F. Vigil, 2010). Furthermore, if weed species are not properly controlled during the fallow period of the rotation, the advantage of increased soil water accumulation may be lost, in addition to decreased soil nutrients such as nitrate-N, which is a critical macronutrient in grain yield and protein formation for HWW (Derksen *et al*., 2002; Holtzer *et al*., 1996; Peairs *et al*., 2005). These negative aspects of fallow use in semi-arid crop production systems have encouraged the intensification of cropping systems to reduce the duration or frequency of the fallow period. However, fallow is still a practice that can be used to increase farm-scale cropping system flexibility in the event of chronic drought to minimize farm-scale loss due to crop failure.

Alternative crop species and rotations have been evaluated across many semi-arid regions of North America for their ecological and economic viability compared to CSF in wheat-fallow or wheat-corn (*Zea mays* L.)-fallow systems (Miller *et al*., 2002b, 2006; Krupinsky *et al*., 2006). Field pea, *Pisum sativum* (L.), (FP) has emerged as a viable fallow alternative in the semi-arid High Plains (HP) and production has increased over the last 10 years (Joshi & Rao, 2017; P. Miller *et al*., 2015; USA Dry Pea & Lentil Council, 2008). This is due primarily to a renewed interest in farm-scale ecology, sustainable grain production practices, the growth of new markets, emergence of plant-based protein products, the short growing season of FP, and the availability of crop insurance (P. R. Miller *et al*., 2002, 2006).

Yellow FP, is a cool-season, annual vining legume native to Southwest Asia (Oelke *et al*., 1991; Pavek, 2012). Yellow FP is commonly planted in mid-March to late April with the harvest of grain in mid-July to early August, depending upon climate trends, seasonal precipitation, and growing region (Oelke *et al*., 1991; Pavek, 2012; Schatz & Endres, 2009). New yellow FP varieties have been developed to adapt to the drier, warm climates of the HP with FP production growing to approximately 367,454 planted hectares in 2018 across the United States (Carlisle, 2015; Cutforth *et al*., 2007; Pavek, 2012; Schatz & Endres, 2009; Smýkal *et al*., 2012). In the semi-arid Northern Great Plains and other water-limited environments, FP has been used in diversified cropping systems to improve precipitation use efficiency (PUE) (Miller *et al*., 2003; Nielsen *et al*., 2005), increase annualized system grain yield, reduce soil erosion rates, and improve soil organic matter over that of CSF (Beckie & Brandt, 1997a; N. Z. Lupwayi & Soon, 2009; Querard *et al*., 2015).

Although available soil water content can be increased with the use of CSF before HWW planting, there is not always an economic benefit to incorporating fallow in a crop rotation. The soil water advantage of implementing CSF may not be financially feasible due to pest pressures, reduced farm net income, and increased weed control costs (Black *et al*., 1981; Dhuyvetter *et al*., 1996a; D. C. Nielsen *et al*., 2005; Stepanovic *et al*., 2016). Additionally, the use of CSF paired with monoculture crop production has been shown to degrade soil health, decrease soil microbiome diversity, and increase proliferation of herbicide-resistant weed species (Dhuyvetter *et al*., 1996b; Anderson *et al*., 1999b; Tanaka *et al*., 2002; Carlisle, 2015). These studies have shown that the long-term application of CSF does not always promote positive ecological advantages while only providing minor short-term economic gains. Previous studies throughout the semi-arid Great Plains have shown that increased farm-scale profitability can be attained by intensifying dryland cropping systems with legumes while benefiting ecological parameters such as the N economy (Peoples *et al*., 2009), soil health (P. R. Miller *et al*., 2002, 2006), and preventing erosion (Anderson *et al*., 1999).

While intensifying a crop rotation usually improves economic or ecological parameters, there are notable concerns in dryland cropping systems that arise when rotations are diversified or intensified. The most noticeable drawback that producers may encounter when removing CSF from a crop rotation is the decrease in plant available water within the effective rooting zone of the previous FP crop, especially if the soil profile has received below-average precipitation during the previous growing season (D. C. Nielsen *et al*., 2005, 2015; Peterson & Westfall, 2004; Smika, 1970). Precipitation events are variable and erratic, both spatially and temporally, throughout the Central HP (Wang *et al*., 2010). Cover crops, alternative small grains, and pulse crops will deplete soil water reserves within their effective rooting depth, depending on growing season precipitation accumulation, soil characteristics, and nutrient availability. Subsequent research has shown that diversified cropping systems can decrease a land unit's PUE (D. C. Nielsen *et al*., 2005). Additionally, if precipitation is abnormally low or non-existent during the fallow period, soil moisture levels may remain too depleted to support the seedling emergence of the subsequent HWW crop. Furthermore, an ineffective weed management program will allow aggressive or prolific broadleaf and grass weed species such as palmer amaranth [*Amaranthus palmeri* (L.) S. Watson], kochia [*Bassia scoparia* (L.) A.J. Scott], and cheatgrass [*Bromus tectorum* (L.)] to proliferate during fallow and to consume valuable soil water accumulated during a CSF period, leaving to question whether water is better used growing a short season grain crop (Stepanovic, 2018). Improvement of ecological parameters and subsequent crop yield by replacing CSF with FP in water-limited eco-regions requires more investigation if FP is going to be a long-term replacement to CSF across the HP region (Gan *et al*., 2003; Krupinsky *et al*., 2006; P. R. Miller *et al*., 2002, 2006; Perry R. Miller *et al*., 2015; Stepanovic *et al*., 2016).

Research outlining the rotational benefits of FP for cropping systems in the Northern Great Plains has been thorough, but the adaptability of this management practice for producers in the semi-arid regions of the HP, such as western Nebraska, has yet to be critically examined (P. R. Miller *et al*., 2003; D. C. Nielsen *et al*., 2005; Peterson & Westfall, 2004; Smika, 1970). Some studies in the semi-arid HP have cast doubt on the positive effects FP and other alternative crops can have on dryland cropping systems (Anderson *et al*., 1999; Dhuyvetter *et al*., 1996a; Lenssen *et al*., 2007b; D. C. Nielsen & M. F. Vigil, 2017; Tanaka *et al*., 2002). Research is needed to determine if positive sustainability trends, such as increased soil organic matter or soil N economy maintenance, can be fostered with the adoption of FP to replace CSF without causing grain yield loss in subsequent HWW crops by possibly increasing the cumulative cropping cycle grain production. The objective of this experiment was to compare FP as a replacement to CSF in a field-scale setting while comparing soil nutrient concentration, soil water content, and subsequent HWW yield between FP and CSF.

MATERIALS AND METHODS

Two locations were selected within the region of current FP adoption in western Nebraska. The West Central Research and Extension Center Dryland Research Farm (41.051819, -100.747874) is located 10.9 km south of North Platte, NE at an elevation of 854 m. The High Plains Agriculture Laboratory and Research Farm (latitude and longitude; 41.232662, -103.016608) is located 13 km north of Sidney, NE at an elevation of 1319 m. The predominant soil series for the three site-years were mapped as the following for each site-year: Sidney 2018 – 2019 is a Keith Aridic Argiustoll; Sidney 2019 – 2020 is a Duroc Pachic Haplustoll; and North

Platte 2018-2019 is a Holdredge Typic Argiustoll. Growing season precipitation and temperature patterns for 2018-2020 paired with 30-year historical means (1988 – 2018) are shown in Figures 1 and 2 for Sidney and North Platte. Growing season and historic precipitation and temperature data was obtained via the High Plains Climate Center ACIS-CLIMOD online data service webpage. Climate data for Sidney, NE was obtained via the ‘Sidney Municipal Airport’ weather station and North Platte, NE climate data was obtained via the ‘North Platte Experiment Station’ weather station. All field sites were managed under a no-till corn program the previous year before FP and CSF plot establishment and contained short, standing corn stubble on the soil surface at the time of FP planting to begin the sequence comparisons for the first growing season. The corn stubble (15 – 20 cm tall) was left intact during the winter months and no tillage was completed between harvest of the previous year’s corn crop and establishment of FP or CSF plots. The experiment was designed as a randomized complete block design with two treatments (CSF – HWW, and FP - HWW) and six replications per location. Each plot contained 83 m^2 of field area with each plot measuring 18 m in length and 5 m in width, resulting in 12 experimental units per site-year. This experiment compared a Corn-CSF-HWW and Corn-FP-HWW crop sequence, starting with the comparison of CSF and FP followed by evaluation of HWW in all plots the following year. This experiment was conducted over two years for each individual site-year with year 1 being the establishment of CSF or FP plots followed by HWW growing in year two to evaluate subsequent effects on the following HWW crop.

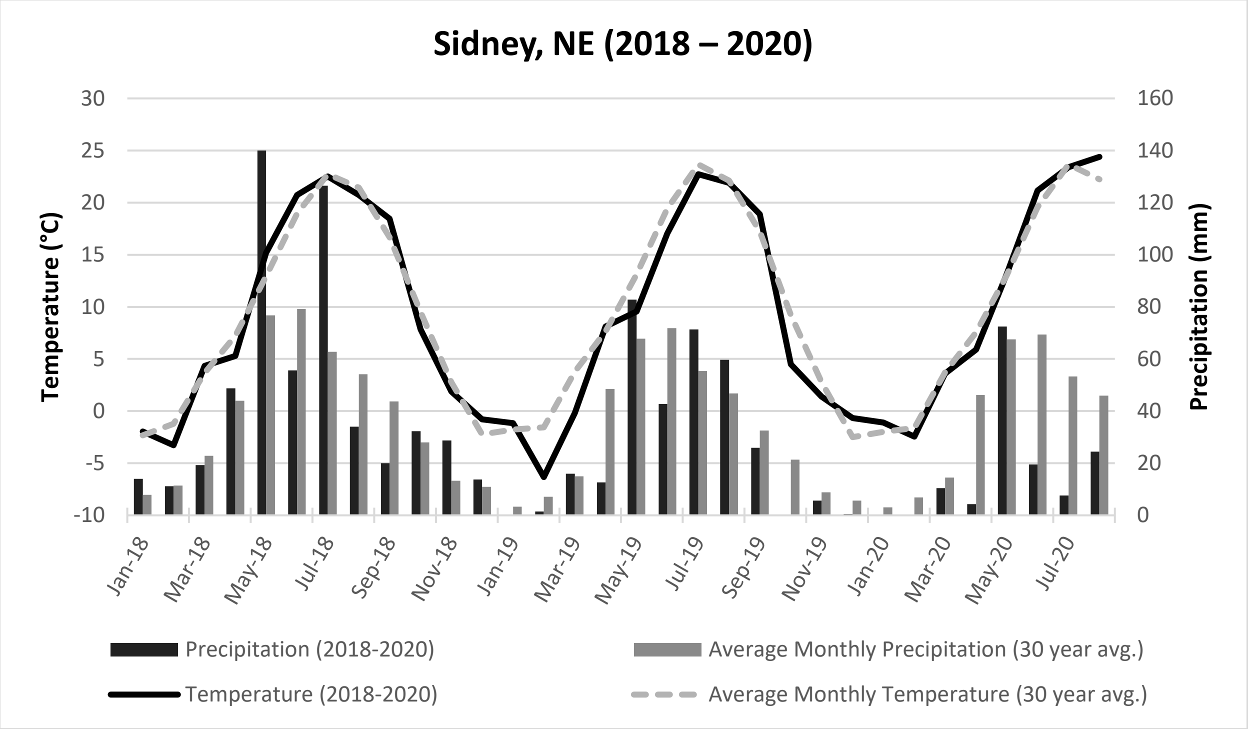

Figure 1. Observed temperature and precipitation from Jan 2018 to Aug 2020 at Sidney, NE along with the historical 30-year mean temperature and precipitation (High Plains Climate Center, 2021).

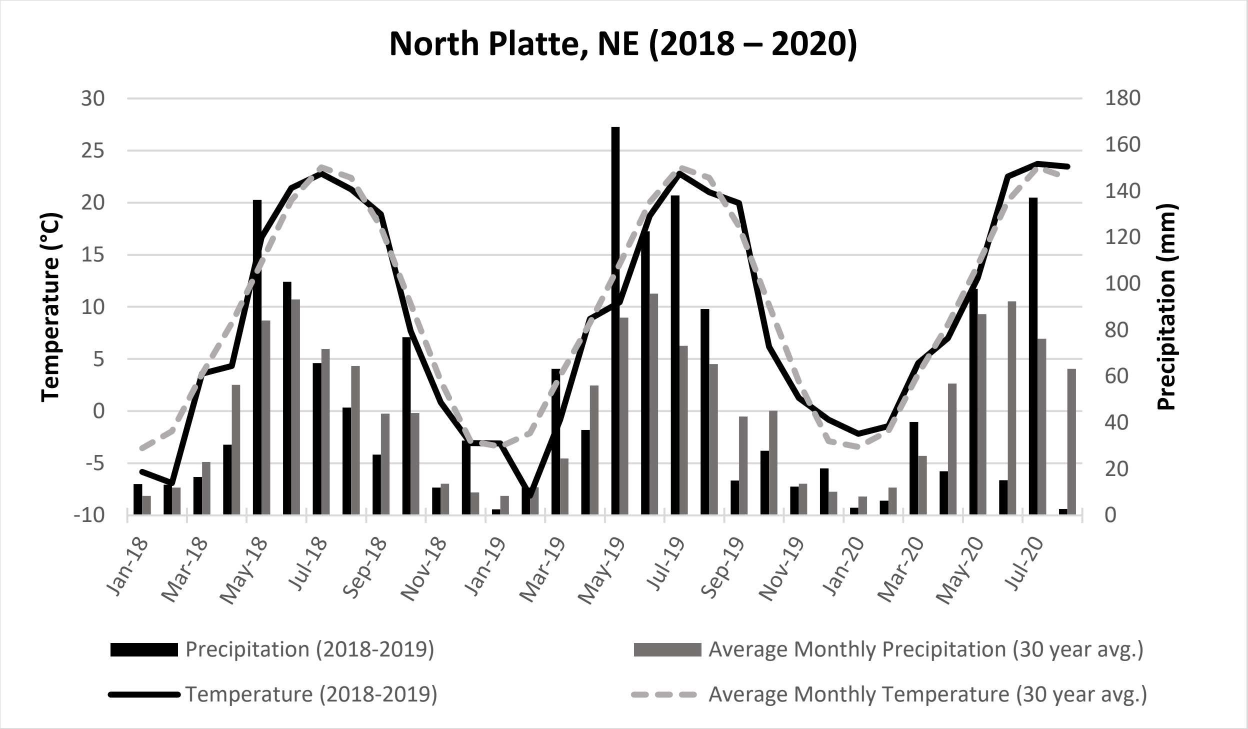

Figure 2. Observed temperature and precipitation from Jan 2018 to Aug 2020 at North Platte, NE along with the historical 30-year mean temperature and precipitation (High Plains Climate Center, 2021).

Field pea plots were planted on 23 Mar 2018 (North Platte), 21 Mar 2018 (Sidney), and 2 Apr 2019 (Sidney) with 'Nette 2010' yellow field pea seed from PULSE USA© (https://www.pulseusa.com/seed). Seeding rate of FP targeted 77 PLS m^{-2} for all site-years, following previously recommended seeding rates for the region (Koeshall *et al*., 2020; Stepanovic *et al*., 2018). The FP was seeded with a SRES experimental plot planter (https://kincaidseedresearch.com/equipment/planters-drills/) with a row spacing of 24 cm and eight total row units. The FP seed was inoculated with Verdesian N-DURE© powder (*Rhizobium leguminosarum* biovar *viceae* 2 × 108 CFU/g) (Verdesian Life Sciences, Cary, NC) at 1.86 kg per 680 kg of seed and treated the day of planting at each location. Pre- and post-emergent herbicides were used to adequately control weeds during the study with rates and application dates found in Supplementary Materials, Tables S1-4. N was applied via liquid urea ammonium nitrate (UAN 32-0-0) to HWW following spring green-up. Supplementary Tables S3-4 detail application timing and rates of UAN. A composite soil test was taken across all plots for each treatment (CSF and FP) at two depths, 0-20 cm and 20-60 cm to obtain a soil fertility baseline at each specific field site to observe change over time between crop sequences. Soil samples were taken in all plots prior to FP planting, following FP harvest, at spring green-up of HWW, and following HWW harvest. Approximately 10 soil cores were randomly sampled from each plot. Each soil core was 1.8 cm in diameter. All 0 – 20 cm soil samples were analyzed for pH (1:1), soluble salts, organic matter concentration, nitrate-N, phosphorus (via Bray P1 test) (P), potassium (K), CO_2 content (via Solvita respiration test), and N mineralization rates (via Solvita respiration test), and all 20-60 cm soil samples were analyzed for nitrate-N. American Agriculture Laboratory, Inc. (McCook, NE) conducted all soil sample analyses for this experiment. Neutron probe access tubes were installed in three replications at each site after emergence of FP plots was observed, were removed at the time of FP harvest, re-installed after HWW seeding, and then removed before harvest of subsequent HWW. Volumetric water content (VWC) [volume of water (m^3) / volume of soil (m^3)] was recorded approximately every two weeks at six depths during the active growing seasons (15, 30, 45, 60, 76, and 91 cm) with a 503TDR Hydroprobe (CPN) (https://cpn-intl.com). Field pea was harvested for grain yield with a Zurn© 150 plot combine harvester on 10 July 2018 (WCREC) and 11 July 2018 and 30 July 2019 (HPAL) with grain yield, test weight, and seed moisture recorded for each plot. All yield observations were adjusted to a common seed moisture of 13%. Hard red winter wheat, Husker Genetics – "Ruth" NE10589, was planted at a seeding rate of 67 kg ha^{-1} at both locations on 9 September 2018 (Sidney), 21 September 2018 (North Platte), and 8 September 2019 (Sidney) with a target stand density of 245 PLS m^{-2}. HWW was seeded at 24 cm row spacing with a SRES experimental plot planter with eight row units. Plots were sprayed with a pre-plant burndown herbicide before HWW planting in 2018 and with a pre-emergent herbicide the following spring in 2019 with a similar protocol followed for HWW again in 2020 at HPAL (Supplementary Tables 1-4).

Harvest of HWW occurred on 26 July 2019 (WCREC), 30 July 2019 (HPAL), and 10 July 2020 (HPAL) with a Zurn© 150 plot combine harvester. After HWW was harvested from CSF and FP plots in the second year of the study sites, final soil samples were taken to assess soil fertility parameters from a depth of 0-20 cm and 20-60 cm from CSF and FP plots with a hand-operated JMC soil core sampler.

Economic analysis to compare the FP-HWW and CSF-HWW crop sequences assumed the market price of FP at \$0.176 kg^{-1} with HWW at \$0.1554 kg^{-1} for the 'average' price model, FP at \$0.4675 kg^{-1} with HWW at \$0.1554 kg^{-1} for the 'high pea' price model; and FP at \$0.176

kg^{-1} with HWW at \$0.281 kg^{-1} for the ‘wheat high’ price model. FP price was obtained from the mean price listed by the Bridgeport, NE farmers’ cooperative grain elevator following the 2019 growing season in an attempt to use the most geographically relevant price for a crop species that is relatively new to the specific growing region of western NE. The elevated FP price of \$0.4675 kg^{-1} for the ‘high pea’ price model was obtained from the 19 Mar 2022 USDA Weekly Bean, Pea, and Lentil Market Review. HWW price for the ‘average’ price model was obtained on 07 Nov 2019 from the Chicago Board of Trade (CBOT). The elevated HWW price for the ‘high wheat’ price model was obtained from the USDA ERS wheat market report for 10 Mar 2022 from the Nov-Dec 2021 reported mean price. Three varying price model examples were used to understand how volatile price changes for a single crop might influence the annualized net profitability for the crop sequence comparisons within each site-year. A ‘below average’ pricing model for HWW or FP was not included as a lower market price for either HWW or FP would have only exacerbated the annualized net losses observed across the three pricing models included. Gross revenue was calculated by multiplying the respective crop (FP or HWW) mean grain yield for each site-year × crop sequence treatment by the above market grain price. In the case of the FP-HWW treatment, system total gross revenue was calculated by summing the mean FP and HWW individual gross revenue. The 2-year system total gross revenue for the CSF-HWW treatment is represented only by the HWW gross revenue, due to no realized monetary return from CSF. Annualized gross revenue was calculated by dividing the two – year system total gross revenue (FP + HWW or CSF + HWW) by number of growing seasons, which is two for this crop sequence comparison. Cost of production for each crop sequence was obtained via the UNL 2022 CropWatch Budgets resource (https://cropwatch.unl.edu/budgets). The cost of production per hectare used in our net profit analysis was \$467.27 for FP, \$847.33 for HWW following CSF, and \$592.50 for HWW following a previous row crop. Overhead, real estate opportunity, and real estate taxes for Nebraska farms were factored into the cost of production rates used for all pricing models. Possible subsidy payments from the Farm Program were not included in this profit/loss analysis.

Field pea grain yield and subsequent HWW yield data were analyzed using R 3.6.1 (R Core Team, 2018) using the 'lmer' package (Kuznetsova *et al.*, 2017) with treatment (CSF vs. FP) and site-year as fixed effects and replication as a random effect. Soil fertility results were analyzed in R 3.6.1 (R Core Team, 2018) using lmer and modeled as a split-plot in time with treatment as the whole plot unit and sample date as the split-plot unit where treatments and site-years were considered fixed effects and replications within site-year as random effects. Volumetric water content results were analyzed in R 3.6.1 (R Core Team, 2018) using lmer as a repeated measure with treatment and site-year as fixed effects with replication as a random effect at each of the six sampling depths.

Crop sequence net profit and annualized system net profit was analyzed in R 4.1.3 (R Core Team, 2022) using the 'lmer' package with site – year and crop sequence as fixed effects and replication as a random effect. Tukey-Kramer HSD pair-wise comparison was completed using the 'multcomp' package in R 4.1.3 (R Core Team, 2022). Due to a significant site – year × crop sequence interaction being present, site – year was centered with crop sequence for accurate Tukey-Kramer HSD post-hoc analysis.

For all response variables, the main effects and interaction terms were evaluated at an $\alpha = 0.10$ level of significance to balance Type 1 and II errors while avoiding the possibility of ignoring differences that would be important to a farmer, especially when comparing differing cropping system programs (e.g. FP - HWW vs CSF – HWW).

RESULTS AND DISCUSSION

Field Pea Yield and Subsequent Winter Wheat Yield

Winter wheat yields between the main effect of FP and CSF were not different ($P = 0.42$) (Figure 3). The main effect of site-years did exhibit varying yields ($P = <0.0001$) with the presence of meaningful interaction between site-year and crop sequence ($P = 0.0005$), with Sidney 2019-2020 chemical summer fallow (CSF) obtaining the greatest grain yield of 3517 kg ha^{-1}, followed by field pea (FP) in the same site-year with 2730 kg ha^{-1}. The presence of the significant interaction term is a result of the varying subsequent HWW yield within the Sidney 2019 – 2020 site-year, in which the CSF – HWW system obtained a greater HWW yield over FP – HWW. There were no differences in FP grain yield among the three site-years ($P = 0.26$), and yields ranged from 1332 – 1605 kg ha^{-1} (Figure 4). Across the three site – year comparisons, the presence of FP in the crop sequence increased total grain yield production by 77% (Sidney and North Platte 2018 – 2019) and 19% (Sidney 2019 – 2020) compared to CSF during the 24-month comparisons between crop sequences (Table 1). Accounting for all site – year × crop sequence combinations, mean combined total grain yield for fallow-wheat totaled 2714 kg ha^{-1} and 3785 kg ha^{-1} for pea-wheat when FP and HWW grain production were summed for the respective sequences (Table 1). Across the three site-years, crop sequences that used FP instead of CSF resulted in greater annualized gross revenue (cumulative gross revenue over two years for each crop sequence divided by the number of years in crop rotation), with Sidney 2019 – 2020 FP obtaining the greatest annualized gross revenue of \$341 ha^{-1}, followed by North Platte 2018 – 2019 FP (\$321 ha^{-1}) and Sidney 2018-2019 (\$284 ha^{-1}). However, increased gross revenue does not directly translate to improved net profit to the farm unit, hence an annualized net profit analysis was completed for the three site – years of this study.

Annualized system net profit changed between site – years and crop sequence ($P =$ <0.0001), for all three pricing models. In the 'average' pricing model, Sidney 2019 – 2020 CSF – HWW has the lowest annualized net losses (-\$150 ha^{-1}), followed by Sidney 2019 – 2020 FP – HWW (-\$189 ha^{-1}) (Table 2).

In the 'pea high' pricing model, FP – HWW resulted in atleast a -\$120 ha^{-1} reduction in net losses (Sidney 2019 – 2020), with the FP – HWW sequence resulted in greater net profits or net loss reductions compared to CSF – HWW (Table 3). North Platte 2018 – 2019 displayed an annualized net profit/loss difference of \$279 ha^{-1}, with FP – HWW resulting in a positive annualized net profit.

In the 'wheat high' pricing model, the elevated HWW price did not result in a clear crop sequence that resulted in greater overall annualized net profit or reduction in annualized net losses with FP – HWW resulting a reduced annualized net losses (North Platte 2018 – 2019), FP – HWW and CSF – HWW resulting in equal annualized net losses, and CSF – HWW resulting in a positive annualized profit (Sidney 2019 – 2020). Within the 'wheat high' pricing model, Sidney 2019 – 2020 CSF resulted in the only site-year × crop sequence combination that produced an annualized net profit back to the farm unit.

Based on the assumed market prices during the term of the experiment, geographically relevant cost of production for each crop sequence, and observed grain yields across the entirety of this experiment, our example shows that there was not any site – year × crop sequence combination that resulted in a positive net return to the farm unit under the 'average' pricing model. However, this annualized net profit/loss analysis is still valuable to dryland crop production operations as local and global grain markets, paired with volatile and unpredictable input costs may result in a net loss to the cropping system. Additionally, the value of this multi-model pricing analysis for annualized system net profit allows the farm unit to identify crop sequences that are more likely to return a net profit under certain market conditions. A farm unit should be able to be structured in such as fashion that their cropping system allows for resiliency and robustness while mitigating as much economic risk as possible.

Annual climate trends and patterns are important to understanding how a dryland cropping system performs during a single crop rotation cycle, given the reliance on precipitation amount and timing paired with monthly temperature. These general climate factors can largely determine the success of an intensified crop rotation and final grain yield for each crop species. The absence of HWW yield differences between FP and CSF at Sidney and North Platte can be attributed to the above-average spring precipitation observed in May 2018 and 2019. However, below-average precipitation during subsequent HWW during the Sidney 2019 – 2020 site-year resulted in decreased HWW yield in previous FP plots compared to CSF (Figures 1 and 2). Due to the increase in annualized grain production with the use of FP over CSF, annualized gross revenue was increased at least \$67.43 ha^{-1} with the use of FP when crop sequence treatments were compared within each site-year (Table 1). Furthermore, FP reduced annualized net losses to the farm unit by \$70 ha^{-1} for North Platte 2018 – 2019 (Table 2). However, in one of three site-years, FP did increase annualized net losses to the farm unit by \$39 ha^{-1} for Sidney 2019 – 2020. Yield results from this experiment showed that HWW yields between crop sequences were not different in two of three site-years, even though the crop sequence was intensified with the presence of another cash crop (Figure 3). Our gross revenue and grain yield results align with previous studies that showed diversification of a cropping system in the Northern or Central

Great Plains can increase annualized grain yield, gross revenue, and/or reduce the farm unit risk exposure by reducing net losses (Tanaka *et al.*, 2002; Schlegel *et al.*, 2017).

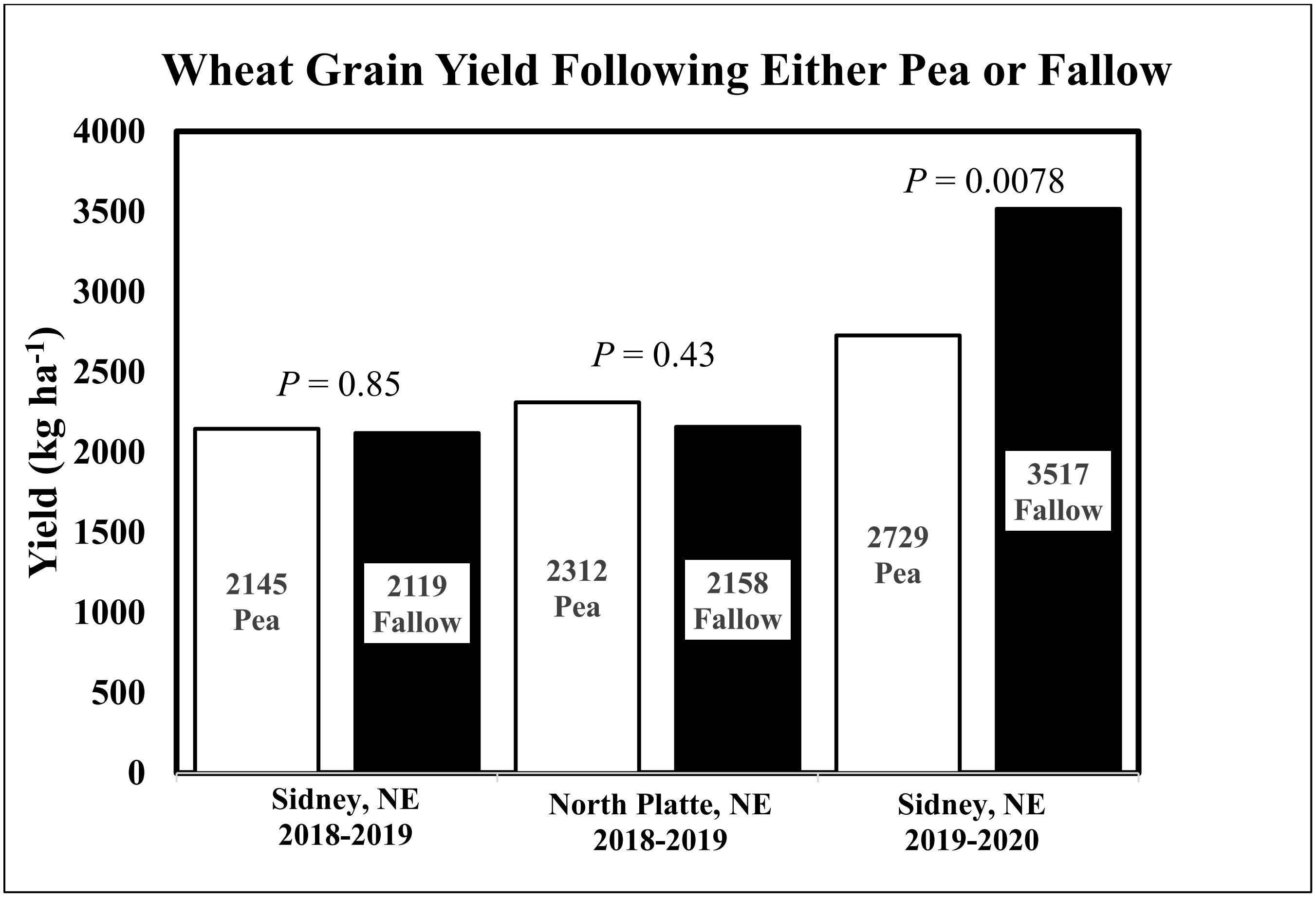

Figure 3. Hard winter wheat grain yield results for all site-year and crop sequence combinations. Means differences for a single site-year is denoted by the p-value result from analysis of variance modeling for FP vs. CSF.

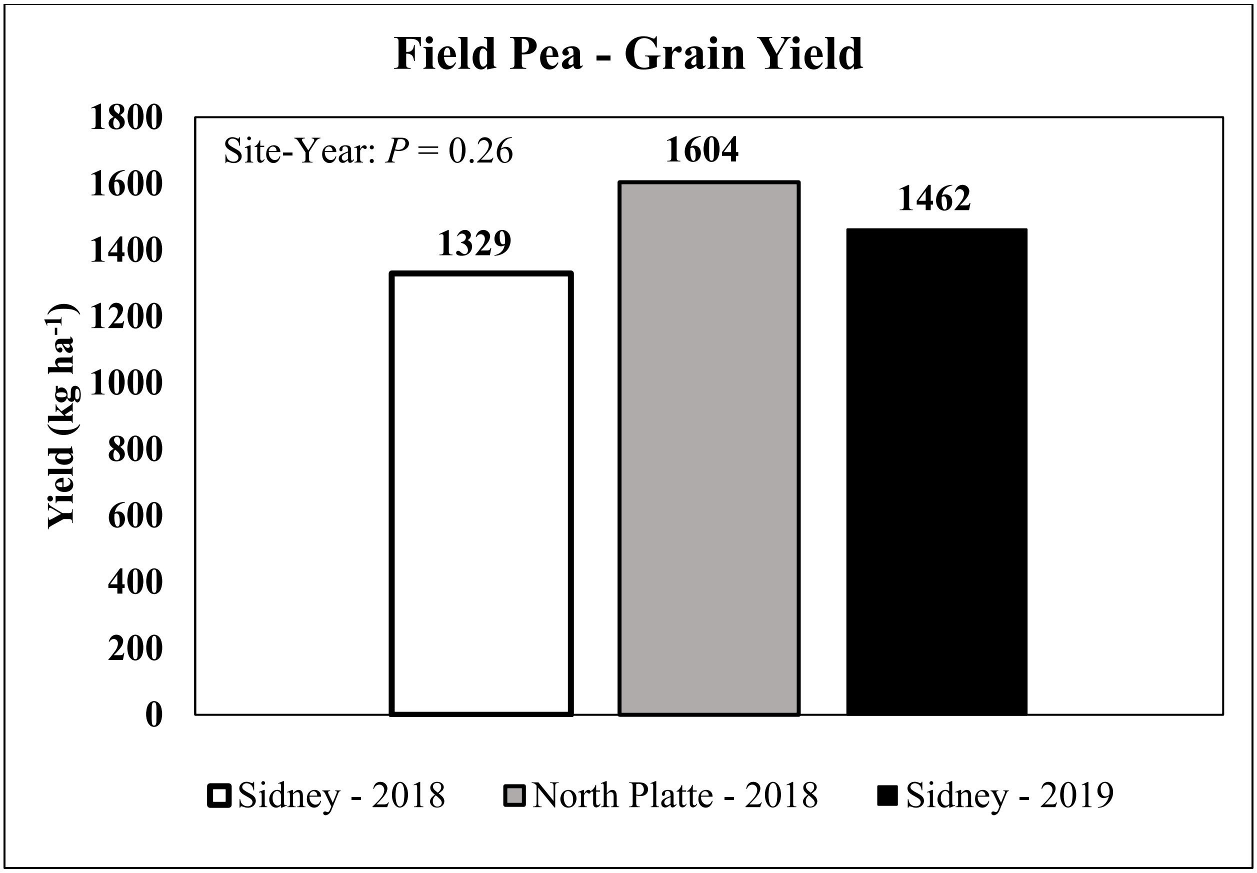

Figure 4. Field pea grain yield results for all site-years during this experiment along with ANOVA results.

Table 1. Mean yield for harvested field pea and hard red winter wheat, gross revenue for field pea and hard red winter wheat, estimated system gross revenue, and estimated system annualized gross revenue for all site-year × crop sequence combinations evaluated in this study in western Nebraska from spring 2018 to summer 2020 for the ‘average’ price model.

Site-Year × Crop Sequence	Field Pea		Winter Wheat		System Total
	Yield	Gross Revenue	Yield	Gross Revenue	Annualized Gross Revenue
	kg ha^{-1}	\$ ha^{-1}	kg ha^{-1}	\$ ha^{-1}	\$ ha^{-1}
SID 2018 – 2019 FP	1329	233	2145	333	283.64
SID 2018 – 2019 CSF	0	0	2119	329	164.67
NP 2018 – 2019 FP	1604	282	2312	359	320.77
NP 2018 – 2019 CSF	0	0	2158	335	167.70
SID 2019 – 2020 FP	1462	257	2729	424	340.70
SID 2019 – 2020 CSF	0	0	3517	546	273.27

*Field Pea price (kg) = \$0.176 (2019 Bridgeport, NE Farmers’ Cooperative)
**Winter Wheat price (kg) = \$0.1554 (11-7-19 via CBOT)
***SID = Sidney, NP = North Platte
****FP = Field Pea, CSF = Chemical Summer Fallow

Table 2. Mean annualized system net profit/loss and post-hoc Tukey Kramer 'Honest Significant Difference' comparisons based on crop prices, estimated cost of production rates, and observed grain yields during the period of this experiment for North Platte and Sidney, NE from 2018 – 2020 for the 'average' pricing model.

Site-Year	Crop Sequence	Net Profit (+) / Loss (-) $ ha^{-1}	Tukey Kramer HSD common letter display
North Platte (2018 - 2019)	Fallow/Wheat	-$273	c
North Platte (2018 - 2019)	Pea/Wheat	-$203	b
Sidney (2018 - 2019)	Fallow/Wheat	-$276	c
Sidney (2018 - 2019)	Pea/Wheat	-$261	c
Sidney (2019 - 2020)	Fallow/Wheat	-$150	a
Sidney (2019 - 2020)	Pea/Wheat	-$189	ab

*Field Pea price (kg) = $0.176 (2019 Bridgeport, NE Farmers' Cooperative)

**Winter Wheat price (kg) = $0.1554 (11-7-19 via CBOT)

Table 3. Mean annualized system net profit/loss and post-hoc Tukey Kramer 'Honest Significant Difference' comparisons based on crop prices, estimated cost of production rates, and observed grain yields during the period of this experiment for North Platte and Sidney, NE from 2018 – 2020 for the 'pea high' pricing model.

Site-Year	Crop Sequence	Net Profit (+) / Loss (-) $ ha^{-1}	Tukey Kramer HSD common letter display
North Platte (2018 - 2019)	Fallow/Winter Wheat	-$273	c
North Platte (2018 - 2019)	Pea/Winter Wheat	$6	a
Sidney (2018 - 2019)	Fallow/Winter Wheat	-$276	c
Sidney (2018 - 2019)	Pea/Winter Wheat	-$114	b
Sidney (2019 - 2020)	Fallow/Winter Wheat	-$150	b
Sidney (2019 - 2020)	Pea/Winter Wheat	-$30	a

*Field Pea price (kg) = $0.4675 (29 Mar 2022 USDA Weekly Bean, Pea, and Lentil Market Review)

**Winter Wheat price (kg) = $0.1554 (11-7-19 via CBOT)

Table 4. Mean annualized system net profit/loss and post-hoc Tukey Kramer 'Honest Significant Difference' comparisons based on crop prices, estimated cost of production rates, and observed grain yields during the period of this experiment for North Platte and Sidney, NE from 2018 – 2020 for the 'wheat high' pricing model.

Site-Year	Crop Sequence	Net Profit (+) / Loss (-) $ ha^{-1}	Tukey Kramer HSD common letter display
North Platte (2018 - 2019)	Fallow/Winter Wheat	-$152	c
North Platte (2018 - 2019)	Pea/Winter Wheat	-$73	b
Sidney (2018 - 2019)	Fallow/Winter Wheat	-$157	c
Sidney (2018 - 2019)	Pea/Winter Wheat	-$141	c
Sidney (2019 - 2020)	Fallow/Winter Wheat	$71	a
Sidney (2019 - 2020)	Pea/Winter Wheat	-$18	b

*Field Pea price (kg) = $0.176 (2019 Bridgeport, NE Farmers' Cooperative)

**Winter Wheat price (kg) = $0.281 (10 Mar 2022 USDA ERS Wheat Report)

In addition to increased system production, FP has been shown to decrease farm-scale financial risk and improve ecological parameters such as soil health and precipitation use efficiency (Beckie and Brandt, 1997; Carr *et al*., 2008; Lupwayi *et al*., 2012). This observation suggests that HWW producers should consider FP as a viable alternative crop to CSF management. However, in this experiment for both Sidney and North Platte during 2018 – 2019, the monthly precipitation during the growing season was greater than the 30-year historic average (1988 – 2018), with Sidney accumulating 192 mm ampersand North Platte 276 mm during the growing season of pea (Figures 1, 2). The above-average precipitation at both sites in the 2018 – 2019 comparison may have mitigated the possible HWW yield reduction of reduced VWC in FP plots during FP grain development, resulting in the non-significant difference in HWW yield between crop sequences for Sidney 2018 – 2019 and North Platte 2018-2019. In general, producers should be aware of the added cost of including a new crop in the system and the challenges that growing FP might bring to the farm-scale operation.

Results from this experiment indicate that opportunity exists to improve farm-scale annualized yield, improve gross revenue, reduce net losses, and diversify species grown on the farm, and in two of three comparisons, without reducing HWW yields in the cereal-based crop rotation (Figures 4-5, Table 1). However, longer-term studies within the semi-arid HP region such as (D. C. Nielsen & M. F. Vigil, 2017) have shown that the inclusion of FP consistently reduces HWW yield, suggesting that the benefit of FP to the cropping system and overall economics is largely dependent upon growing season precipitation and available moisture (Figures 1-2). Overall, across all three pricing models, FP – HWW resulted in five site-year × crop sequence combinations that resulted in a greater annualized net profit or reduction in net losses over CSF – HWW, with CSF – HWW resulting in only two site-year × crop sequence combinations that resulted in a greater annualized net profit or reduction in net losses over FP - HWW, and two site-year × crop sequence combinations that did not show any annualized net profit/loss differences between FP and CSF sequences (Tables 2 – 4).

Volumetric Water Content

For both iterations of this experiment at Sidney, most of the water was in the top half of the observed soil profile, whereas at North Platte in 2018 – 2019, most of the water was in the bottom half of the observed soil profile. These differences are most likely due to environmental differences between sites such as soil texture, annual climate patterns, and historical crop and soil management (Tables 4, 5).

Volumetric water content changed throughout the cycle, evident by the site-year × measurement date interactions across all depths of VWC measurement, regardless of the crop sequence, suggesting climate factors such as monthly precipitation dictated soil water content levels more so than the specific crop water need of FP compared to CSF (Tables 4 - 5, Figure 5). The VWC was not different at any of the six sample depths (15, 30, 45, 60, 76, and 91 cm) for the main effect of crop sequence. The Sidney 2019 – 2020 study site consistently displayed greater amounts of soil water compared to North Platte and Sidney in 2018 – 2019 (Table 4 - 5).

Table 4. Analysis of variance for volumetric water content (VWC) at each depth across three site-years in western Nebraska with VWC measurement beginning at the establishment of FP and CSF plots and ending at harvest of the subsequent HWW crop the following growing season.

Source of Variation (SV)	**Depth of Volumetric Water Content Measurement (cm)**					
	15	**30**	**45**	**60**	**76**	**91**
	Volume of water (m^3) / Volume of Soil (m^3)					
Site-Year (SY)	**0.0003**	**<0.0001**	**<0.0001**	**0.0018**	**0.0843**	**<0.0001**
Crop Sequence (CS)	0.99	0.57	0.56	0.72	0.89	0.82
Measurement Date (MD)	**0.0974**	0.26	0.27	0.44	0.29	0.36
SY × CS	0.24	0.57	0.53	0.80	0.91	0.11
SY × MD	**0.0004**	**<0.0001**	**<0.0001**	**0.0022**	**0.0896**	**<0.0001**
CS × MD	0.99	0.57	0.56	0.72	0.89	0.82
SY × CS × MD	0.24	0.58	0.52	0.82	0.93	0.103

Table 5. The least-square means and Tukey HSD results tested for each measured VWC depth among site-year × crop sequence combinations across all measurement dates, starting at seeding of FP and ending at harvest of subsequent HWW.

Site-Year × Crop Sequence	**Depth of Vol. Water Content Measurement (cm)**					
	15	**30**	**45**	**60**	**76**	**91**
	Volume of water (m^3) / Volume of Soil (m^3)					
North Platte 2018 – 2019						
Field Pea	0.128 c	0.195 b	0.187 bc	0.279 a	0.301 a	0.299 a
Chemical Summer Fallow	0.175 bc	0.290 ab	0.289 ab	0.344 a	0.320 a	0.319 a
Sidney 2018 – 2019						
Field Pea	0.355 b	0.314 c	0.265 d	0.232 c	0.186 c	0.137 c
Chemical Summer Fallow	0.365 ab	0.389 b	0.327 c	0.270 b	0.229 b	0.221 b
Sidney 2019 – 2020						
Field Pea	0.502 a	0.487 ab	0.466 ab	0.483 a	0.488 a	0.444 a
Chemical Summer Fallow	0.516 a	0.524 a	0.503 a	0.465 a	0.453 a	0.469 a

*significance of treatment effects and interaction evaluated at $\alpha = 0.10$

**Tukey Kramer HSD common display letters within a column denote the individual means comparisons with similar letters being not statistically different from one another

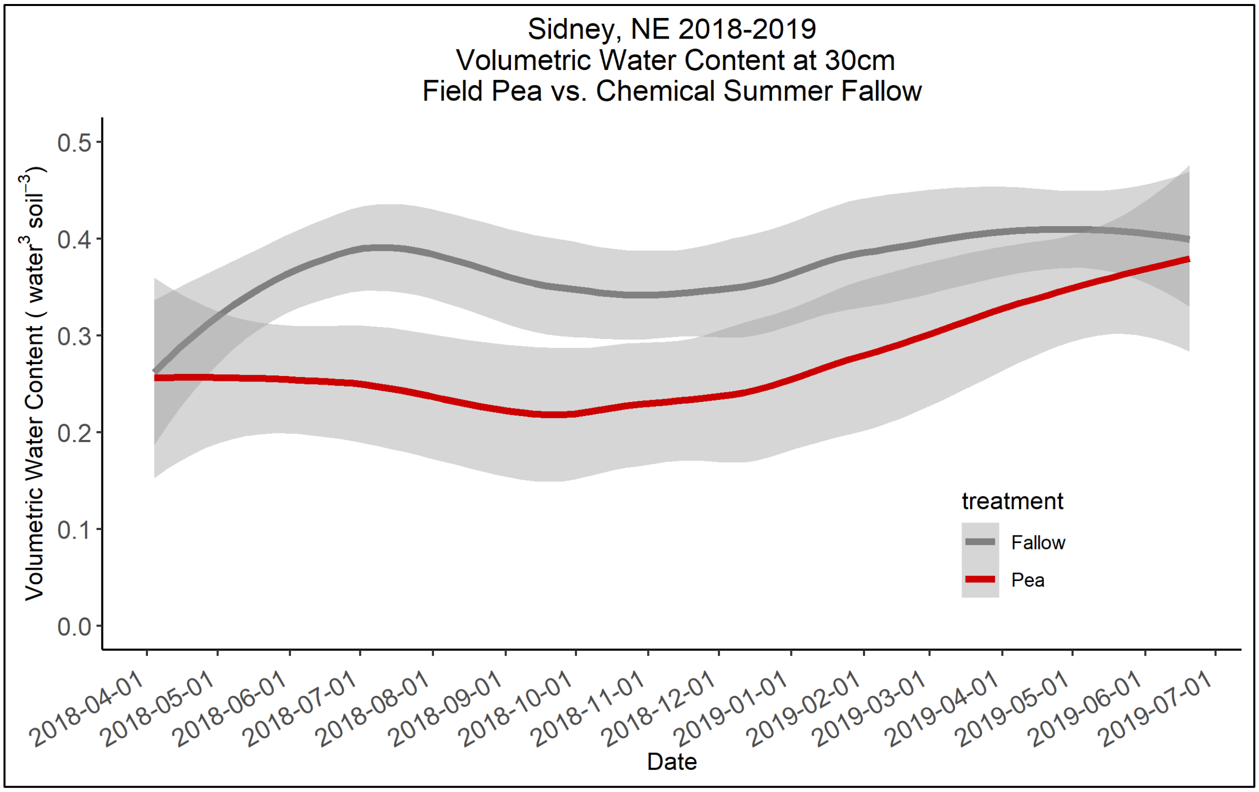

Figure 5. Volumetric water content at 30 cm measured from FP planting through the harvest of subsequent hard red winter wheat grain crop at Sidney, NE 2018 – 2019 with 90% CI bands.

At Sidney 2018 – 2019, 90% confidence intervals show that VWC was only different between CSF and FP at the 30 cm depth from June 1, 2018, to Nov 1, 2018, which corresponds to the time of field pea pod development through the emergence of HWW in the fall (Figure 5). Above-average precipitation during May and July of 2018 helped to recharge the soil within the effective rooting depth of FP during the greatest period of water use by FP, resulting in no observed differences between crop sequences at any sampling depths by mid-November of 2018, according to the 90% CI bands (Figure 5)(Tables 4 – 5). This observation of VWC showing a difference at the 30 cm sampling depth parallels previous research showing the root growth distribution of field pea occurring mainly in the top 0.23 m across multiple water deficits schedules for both dryland and irrigated systems (Benjamin & Nielsen, 2006; D. C. Nielsen & M. F. Vigil, 2018b). Although, Benjamin & Nielsen (2006) found that pea roots are found to grow deeper into the soil profile under dryland conditions, with 34% of the root system below 0.23 m compared to only 20%. However, still 66% of pea roots were found in the top 0.23 m of the soil profile, suggesting that FP depend upon on the soil moisture located in the upper portions of the plants effective rooting depth.

While this study focuses on soil water patterns at 30 cm, a previous long-term crop sequence study conducted by D. C. Nielsen & M. F. Vigil (2018a) found that FP extracted soil water to 120 cm, far outside of the usual effective rooting depth for FP, which resulted in less available soil water for the subsequent HWW crop that depends upon soil water reserves deeper in the soil profile, especially in a semi-arid dryland cropping system. VWC at 30 cm was greater for CSF at time of subsequent HWW seeding, however this reduced availability of soil moisture did not reduce subsequent HWW grain yield for Sidney 2018 – 2019 or North Platte 2018-2019 (Figures 3, 5, 6). However, subsequent HWW yield was reduced by FP compared to CSF at Sidney 2019 – 2020 due to the presence of drought that influenced VWC in both systems (Figure 7). Our HWW yield reduction for Sidney 2019 – 2020 following FP is consistent with what D. C. Nielsen & M. F. Vigil (2017) observed following the completion of a long-term crop sequence study in northeast Colorado in which FP consistently decreased HWW yields via reduced soil water availability.

While winter recharge is important to dryland cropping systems, during a drier year that is more typical to the region, winter recharge might not have been able to fully return soil water content of the field pea plots into equilibrium with chemical summer fallow plots at the time of HWW harvest. At North Platte 2018 – 2019, 90% confidence intervals show that VWC was different at the 30 cm soil depth after 1 July 2018, until 1 September 2018, which corresponds to the final maturation of FP grain to the planting of HWW in the fall of 2018, respectively (Figure

6). Despite the reduction in soil water content after FP, the wheat grain yield was unaffected compared to the CSF plots, except at Sidney 2019 – 2020.

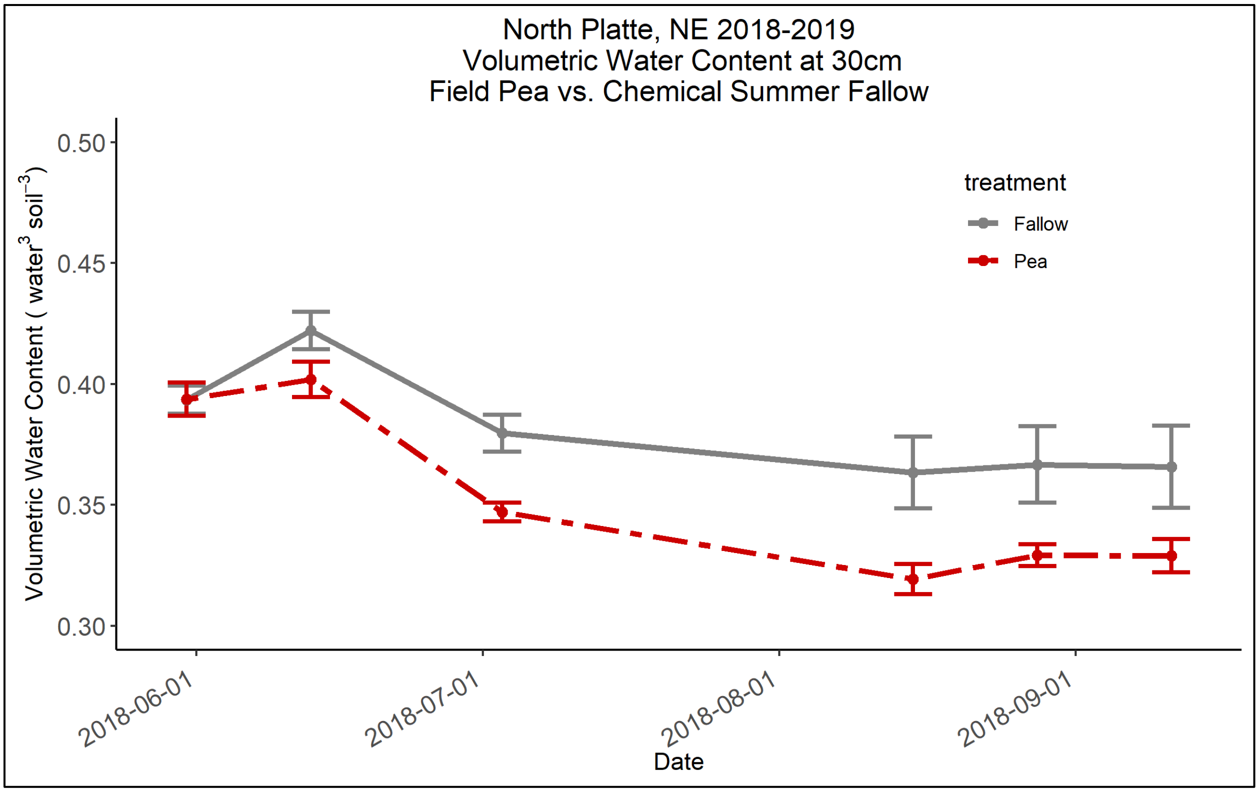

Figure 6. VWC at 30 cm approximately 45 days following FP planting through the maturation of the subsequent HWW grain crop at North Platte, NE 2018 – 2019 with 90% CI error bars.

Precipitation varied in amount and intensity over the 18 months of these studies and can be a significant contributing factor to the overall performance of dryland cropping systems (Figures 1, 2) (Black *et al*., 1981; D. C. Nielsen *et al*., 2005; Peterson & Westfall, 2004; Smika, 1970). As an example, D. C. Nielsen *et al*. (2015) showed that subsequent crop yields are largely determined by the received precipitation and evaporative demands experienced during the previous crops growing period, in this case cover crops. Literature notes that the variability of regular precipitation paired with high evapotranspiration levels during the growing season as well as more predictable precipitation from fall through early spring has encouraged the use of fallow to maintain crop yields in water-limited environments (Black *et al*., 1981; D. C. Nielsen *et* *al*., 2005; Peterson & Westfall, 2004; Schillinger, 2017; Smika, 1970). However, this experiment shows that during the presence of adequate winter recharge and regular growing season precipitation, intensification of a wheat-corn-fallow system with FP improves annualized gross revenue and overall cumulative grain yield. Other research indicates that when precipitation allows, CSF can profitably and ecologically be replaced by FP (Dhuyvetter *et al*., 1996a; Hansen *et al*., 2012; Lenssen *et al*., 2007a; D. C. Nielsen *et al*., 2005; Peterson & Westfall, 2004).

Nielsen and Vigil (2017) demonstrated that there can be large differences in VWC between non-FP and FP cropping systems in terms of available soil water at HWW planting following FP harvest. Our observations confirm this finding as VWC was different between crop sequences at planting time of HWW at both Sidney and North Platte in 2018 (Figures 5, 6). However, Miller *et al*., (2002a) exhibit the positive benefits of integrating field pea in a dryland cropping system as FP because it has a greater water use efficiency compared to spring wheat. Volumetric water content trends for Sidney 2019 – 2020 during the FP growing season followed similar patterns as Sidney in 2018 – 2019, except for the dramatic VWC decrease observed in 2020 due to drought during the growing season, as shown within the 30 cm depth measurement (Figure 7)(Tables 4 – 5). Due to an abnormally dry growing season in 2020 and poor winter recharge, both crop sequences VWC decreased at a similar rate, mitigating any possible VWC differences that might have lasted due to the water use during FP grain formation.

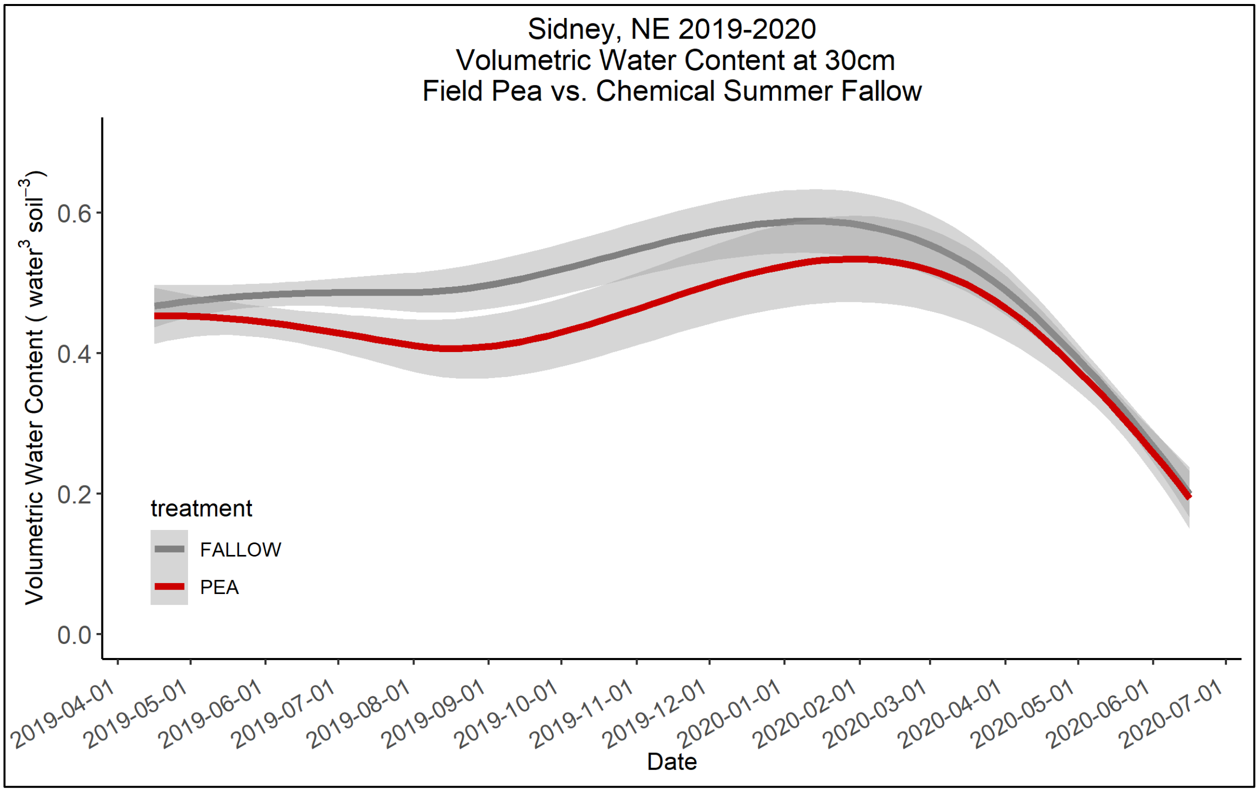

Figure 7. VWC at 30 cm from FP planting through subsequent HWW wheat harvest at Sidney, NE 2019 – 2020 with 90% CI bands.

Had above-average precipitation not occurred during the growing season in 2018 and 2019, CSF plots may have had greater availability of water as HWW entered the reproductive stages of plant development, and a yield difference between CSF and FP plots may have been observed (D. C. Nielsen & M. F. Vigil, 2017, 2018b, 2018c). Even though 42% of accumulated precipitation during CSF is used for future plant uptake with the remainder lost to deep percolation or evaporation, that amount can be significant when in severely water-limited environments (Anderson *et al.*, 1999). However, the percent of accumulated precipitation during the CSF or other fallow period may vary drastically, depending upon soil and climate parameters (D. C. Nielsen & M. Vigil, 2010; Tanaka & Aase, 1987). Warmer growing season conditions paired with below-average precipitation might show greater differences between CSF and FP when analyzing soil VWC in future comparisons. Although results show that HWW yields were not different between crop sequences in above-average precipitation cycles, annualized grain yield was not greater with the use of CSF versus FP in the presence of an abnormally dry growing season (Sidney 2019 – 2020). Producers could adjust the crop rotation depending on the available soil water before the start of the next growing season. With this type of strategy, producers can “flex” to best fit the current growing season climate conditions and available soil water stored in the effective rooting zone of their next crop (Anderson *et al*., 1999; Hansen *et al*., 2012; D. C. Nielsen *et al*., 2011; D. C. Nielsen & M. Vigil, 2017, 2018a). However, this largely depends upon the precipitation realized following HWW seeding, as the value of growing season precipitation outweighs stored soil moisture for the newly seeded crop.

Soil Fertility

Among all three site-years, the main effect of crop sequence did not result in soil nutrient content differences, however, the interaction effect of site-year × measurement date did result in organic matter and nitrate-N differences, primarily due to variations among field sites and temporal nutrient cycling (S.M Table 4, Table 6). While temporal nutrient cycling should be expected in almost any crop sequence or crop rotation experiment, the strongest controlling factor for soil nutrients is the individual, unique variation among field sites, even with the presence of different fertility needs between CSF and FP, in addition to the subsequent HWW crop. Across the various soil parameters tested, except potassium (K) and N mineralization rate, there were differences among site-years (Table 6). For the varying soil parameters tested, Sidney 2018 – 2019 displayed the highest soil fertility levels in general, especially nitrate-N. While Sidney 2018 – 2019 had the highest nitrate-N levels across time, this did not result in greater HWW grain yield. In terms of management, the additional application of UAN in the spring of 2020 on HWW at Sidney may have resulted in the elevated HWW grain yields observed in 2020 compared to other site-years (S.M. Table 4, Figure 3). However, the increased N availability at Sidney in 2018-2019 might have increased subsequent HWW grain protein, as soil N and additional application of N from synthetic sources has been shown to be a driver of increased protein formation, which is a management strategy for wheat growers in the NGP that can access markets that reward farmers for growing high protein grain (Abedi *et al*., 2011; Brown *et al*., 2005; Holford *et al*., 1992; Vaughan *et al*., 1990). Based on our results, soil organic matter may have played a larger role in elevating subsequent HWW yield as Sidney 2019-2020 displayed the highest soil organic matter content, paired with the second-highest nitrate-N levels and a desirable soil pH level for optimum nutrient uptake and plant growth (Table 6).

Table 6. Least square means and Tukey Kramer HSD results for each measured soil fertility parameter among site-year × crop sequence combinations.

Site-Year × Crop Sequence		Soil pH	Organic Matter	Nitrate-N	Phosphorus (Bray P1)	Potassium	N Mineralization (Solvita Incubation)
		1:1 method	g kg soil^{-1}	kg ha^{-1}	ppm	ppm	kg ha^{-1} year^{-1}
NP 2018 – 2019							
	FP	5.09	166 c	12 b	111.6 a	524	18.9
	CSF	5.09	166 c	12 b	105.8 a	514	15.9
SID 2018 – 2019							
	FP	6.79	181 b	32 a	11.4 b	626	50.9
	CSF	6.90	179 b	35 a	11.5 b	615	48.6
SID 2019 – 2020							
	FP	6.63	224 a	15 b	19.3 b	749	45.2
	CSF	6.52	228 a	23 b	21.3 b	753	34.4

*Significance of treatment effects and interaction evaluated at α = 0.10
**FP = Field Pea, CSF = Chemical Summer Fallow
***All soil fertility results above are taken from the 0-20 cm samples

While FP may require the application of synthetic N, Walley *et al.* (2007) found that FP and other pulse crops positively contribute to the N economy of a cropping system in the Northern Great Plains when a cropping system is evaluated over a long period. An example of a legume benefitting the N economy and improving nitrogen mineralization rates following the harvest of FP is what was seen in Sidney in 2019 – 2020 (Figure 8). While FP can positively contribute to the N economy of a cropping system, the rotational benefit of legumes in the cropping system is weighted toward non-N benefits. Approximately 92% of the rotational benefit of field pea is due to improved soil structure, reduced weed densities, increased organic matter, or improved water holding capacity (Beckie & Brandt, 1997a; Querard *et al*., 2015; Stevenson & Kessel, 1996; Vos & Van Der Putten, 2001; Walley *et al*., 2007). Previous studies show that soil fertility and soil health improvements are not fully realized and/or significant until multiple cycles of the intensified crop rotation have been completed (Cotton & Acosta-Martínez, 2018; Govaerts *et al*., 2007; Newton Z. Lupwayi *et al*., 2012; Van Rhoon *et al*., 2004; Wright & Anderson, 2000). As an example, a study completed by Acosta-Martínez *et al.* (2007) showed that after 15 years, overall soil quality, especially microbial communities, was improved with the diversification of crop species in a rotation and a reduction in fallow frequency.

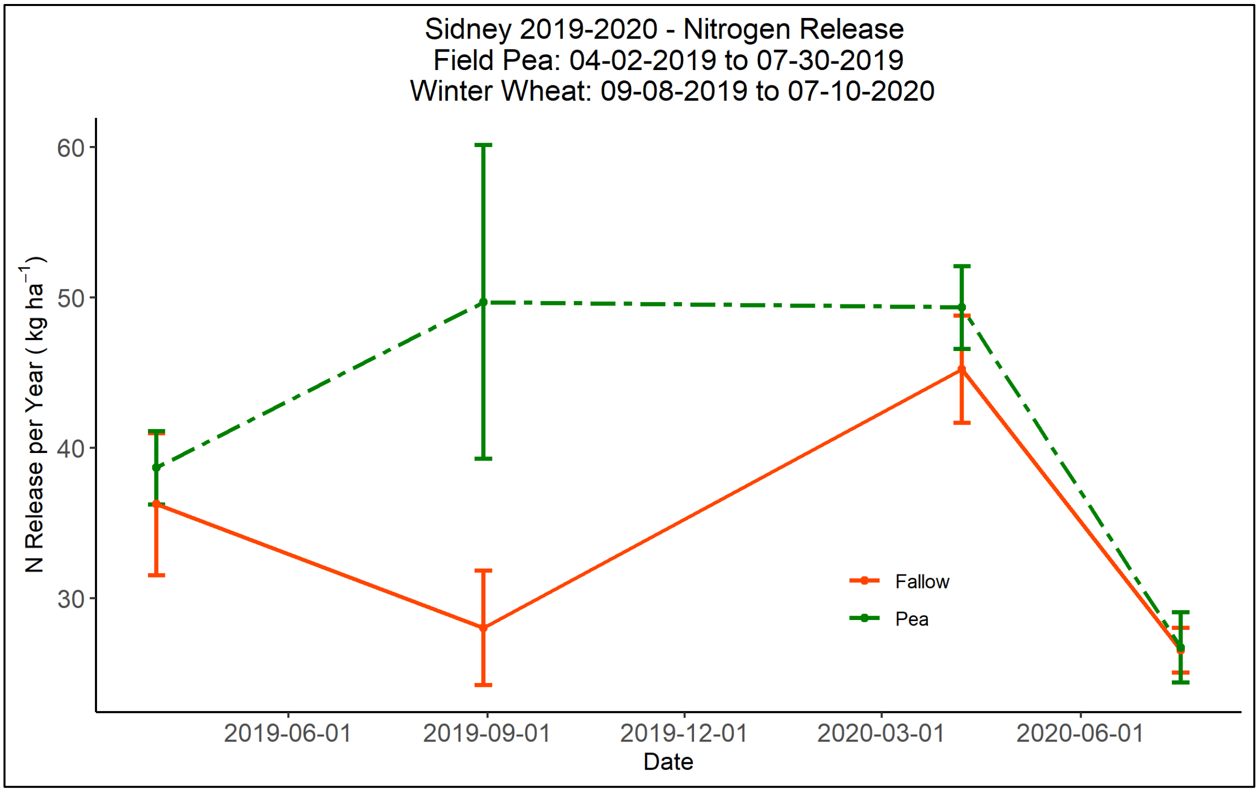

Figure 8. N mineralization rate (kg ha^{-1} yr^{-2}) dynamics over time as influenced by chemical summer fallow and field pea from time of field pea planting through hard red winter wheat harvest at Sidney, NE 2019 – 2020.

The presence of FP at Sidney 2019 – 2020 resulted in a higher level of estimated soil microbial activity and respiration (via Solvita incubation) and increased organic nitrogen release rates compared to soil managed under CSF, following FP harvest at Sidney in 2019 and during HWW development into fall of 2019 (Figure 8). Although microbial activity varied across time and changed with the inclusion of FP, SOM did not change across time or due to crop sequence, although SOM did vary among site – years (Table 6). N mineralization rate was greater for FP after the harvest, though rates returned to similar values by the end of the experimental cycle. Thus, there is a short-term rotational benefit of incorporating a legume species into a crop rotation with leftover crop residue to stimulate increased organic nitrate mineralization. Monthly soil temperature and moisture trends throughout the year might influence the rate of FP residue decomposition that leads to higher N release. In this case, soil temperature and moisture alone fail to explain the increase in soil carbon following FP harvest and into the 2018-2019 winter as soil temperatures declined. Soil carbon content and N mineralization rates increased following FP harvest in 2019 at Sidney, suggesting that FP residue was still present during vegetative HWW growth (Figure 8). Increased soil microbial activity and diversity from intensification and/or diversification of a cropping system could benefit the following HWW crop. In previous studies, improvement of soil microbial communities results in increased soil health, improved soil aggregation, and other physical or biological improvements to the soil profile, resulting in a holistically improved cropping system and soil structure (Acosta-Martínez *et al*., 2007; N. Z. Lupwayi *et al*., 1998; Newton Z. Lupwayi *et al*., 2012).

This experiment only evaluated one cycle of a crop sequence and not multiple cycles of replacing CSF with FP in an HWW-based system. However, Lupwayi and Soon (2009) showed that in a comparison between legume and non-legume crop species, N release rates following legume residue was greater compared to non-legume residue in long-term crop rotations. This might explain why there were not consistent difference across time between crop sequences and subsequent N mineralization. Overall, even though FP did reduce nitrate-N during grain development, the active decomposition of the additional residue and elevated N mineralization resulted in a net-equal N economy for HWW between CSF and FP plots for the 2019-2020 Sidney site (Figure 9). The increased N mineralization rates in FP plots might have also been a factor that resulted in no observed differences in HWW yield between CSF and FP plots, even in the presence of decreased inorganic nitrate-N in FP plots.

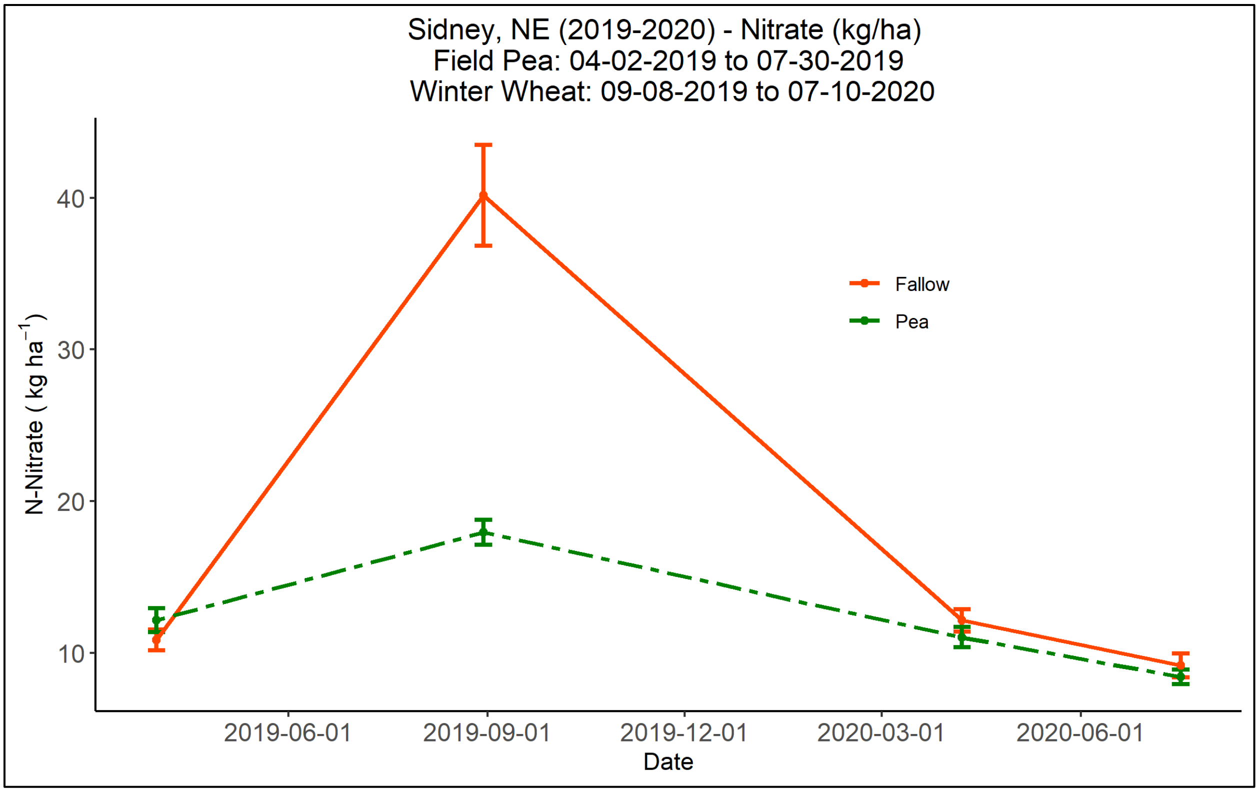

Figure 9. Observed soil nitrate-N (kg ha^{-1}) dynamics over time as influenced by chemical summer fallow and field pea from time of field pea planting through hard red winter wheat harvest at Sidney, NE 2019 – 2020.

The comparison of soil nutrient contents between FP and CSF across time for the three site-years suggests that fertility programs would not need drastic alteration before the subsequent crop is planted, which is a positive outcome as increasing cropping intensity would not necessarily mean greater soil fertility inputs, and in many instances, would mean reduced fertility inputs due to FP positive impact on a systems N economy (Beckie & Brandt, 1997a; Peoples *et al*., 2009; Walley *et al*., 2007). The opportunity to decrease N application from synthetic sources is possible with intensified crop rotations that incorporate legumes, such as FP, as presence of grain markets that pay for elevated grain protein in HWW may reward farmers that include FP in their cropping system as high yield, high protein cereals require high availability of N in cropping systems across the CGP and NGP (Beckie & Brandt, 1997b; Brown *et al*., 1994; Gan *et al*., 2003; P. Miller *et al*., 2015). While the overall soil parameter differences can be attributed to the unique soil texture and site-specific environmental differences, there does not seem to be any short-term evidence that the intensification of a W-C-F or W-F cropping system with FP will negatively influence subsequent HWW crop development and final grain yield. Additionally, this experiment demonstrates the temporal nature of soil nutrient cycling during a single cropping cycle, as shown in Figure 9 with N dynamics across a single cycle at Sidney 2019 – 2020 (Aulakh *et al*., 1991; Havlin *et al*., 1990). Regardless of the crop sequence, the overwhelming majority of soil parameters tested across the site-years show that soil nutrient cycling is due to annual variations such as climate and site-specific characteristics that are the main drivers influencing soil fertility parameters in a short-term experiment.

CONCLUSIONS

In previous studies, increasing crop species diversification, including legume species such as FP, or reducing fallow periods increased the long-term sustainability and improved farm-scale ecological parameters such as soil fertility or PUE (N. Z. Lupwayi & Soon, 2009; D. C. Nielsen & M. F. Vigil, 2017, 2018a; Peoples *et al*., 2009; Querard *et al*., 2015; Tanaka *et al*., 2002). This experiment increased our understanding of the ecological and economic response that FP can have in a dryland cropping system compared to traditional CSF in cereal-based systems, which can be used to establish and achieve the successful application of a more diverse and profitable cropping system for the challenging and harsh climate found in the semi-arid HP region.

Overall, we found that in years with average or above-average precipitation, replacing CSF with FP had no detectable effect on subsequent HWW grain yield, except at Sidney 2019 – 2020, where HWW yields were greater for CSF than FP (Figure 3). Soil moisture differences that were observed between CSF and FP during the fallow replacement season returned to a similar VWC level following the seeding of HWW, even under abnormally low precipitation periods, such as Sidney in 2020 during subsequent HWW growth. Soil fertility also was not significantly different between the main effects of CSF and FP, though there is some evidence that FP plots showed greater nitrogen mineralization, primarily from the breakdown of FP below-ground residue. From an economic standpoint, the inclusion of FP in the rotation increased gross revenue and may have a stabilizing impact on farm income over the long term by spreading out risk between grain markets (P. R. Miller *et al*., 2015). Additionally, in two of three site – year comparisons between CSF and FP for the 'average' pricing model, the presence of FP resulted in reduced or similar annualized system net losses to the farm unit, leading to the possibility that FP may help protect farm systems during periods of reduced grain prices, especially within wheat markets. Out of nine site-year comparisons, FP – HWW either produced greater annualized net returns or reduced annualized net losses compared to CSF – HWW in five site-year comparisons, contrasted with CSF – HWW only resulting in better annualized net profits or reduced net losses in two site-year comparisons. However, CSF – HWW at Sidney 2019 – 2020 in the 'wheat high' pricing model resulted in the greatest annualized net profit across all three economic pricing models, at \$70.50 ha^{-1} (Table 4).

Further research on the effect of replacing CSF with FP is needed to determine if normal to below-average precipitation patterns influence the ecological and economic feasibility of intensifying wheat-based systems with FP throughout the semi-arid HP of western NE. Furthermore, while this experiment shows that there is opportunity to move away from CSF use if adequate precipitation is present during the growing season, we recognize that a long-term crop sequence study is needed for the HP of western Nebraska to determine the long-term influence of FP compared to CSF on soil water, soil fertility, and farm-scale economic returns.

ACKNOWLEDGMENTS

This study was partially funded by the North-Central Sustainable Agriculture Research and Education program (NC-SARE).

LITERATURE CITED

Abedi, T., Alemzadeh, A., & Kazemeini, S. A. (2011). Wheat yield and grain protein response to nitrogen amount and timing. *Australian Journal of Crop Science*, *5*(3), 330–336. https://search.informit.org/doi/abs/10.3316/informit.279825257779534

Acosta-Martínez, V., Mikha, M. M., & Vigil, M. F. (2007). Microbial communities and enzyme activities in soils under alternative crop rotations compared to wheat-fallow for the Central Great Plains. *Applied Soil Ecology*, *37*(1–2), 41–52. https://doi.org/10.1016/j.apsoil.2007.03.009

Anderson, R. L., Bowman, R. A., Nielsen, D. C., Vigil, M. E., & Aiken, R. M. (1999). Alternative Crop Rotations for the Central Great Plains. *Journal of Production Agriculture*, *12*(1), 95–99. https://doi.org/10.2134/jpa1999.0095

Anderson, R. L., Bowman, R. A., Nielsen, D. C., Vigil, M. F., Aiken, R. M., & Benjamin, J. G. (1999). Alternative crop rotations for the central Great Plains. *Journal of Production Agriculture*, *12*(1), 95–99. https://doi.org/10.2134/jpa1999.0095

Aulakh, M. S., Doran, J. W., Walters, D. T., Mosier, A. R., & Francis, D. D. (1991). Crop residue type and placement effects on denitrification and mineralization. *Soil Science Society of America Journal*, *55*(4), 1020–1025. https://doi.org/10.2136/sssaj1991.03615995005500040022x

Badaruddin, M., & Meyer, D. W. (1994). Grain legume effects on soil nitrogen, grain yield, and nitrogen nutrition of wheat. *Crop Science*. https://doi.org/10.2135/cropsci1994.0011183X003400050030x

Beckie, H. J., & Brandt, S. A. (1997a). Nitrogen contribution of field pea in annual cropping systems. 1. Nitrogen residual effect. *Canadian Journal of Plant Science*, *77*(3), 311–322. https://doi.org/10.4141/P96-161

Beckie, H. J., & Brandt, S. A. (1997b). Nitrogen contribution of field pea in annual cropping systems. 1. Nitrogen residual effect. *Canadian Journal of Plant Science*, *77*(3), 311–322. https://doi.org/10.4141/P96-161

Benjamin, J. G., & Nielsen, D. C. (2006). Water deficit effects on root distribution of soybean, field pea and chickpea. *Field Crops Research*, *97*(2–3), 248–253.

https://doi.org/10.1016/j.fcr.2005.10.005

Black, A. L., Brown, P. L., Halvorson, A. D., & Siddoway, F. H. (1981). Dryland cropping strategies for efficient water-use to control saline seeps in the northern great plains, u.s.a. *Developments in Agricultural Engineering*, *2*(C), 295–311. https://doi.org/10.1016/B978-0-444-41999-6.50020-3

Brown, B., Westcott, M., Christensen, N., Pan, B., & Stark, J. (1994). Nutrient management for hard wheat protein enhancement. *Journal of Soil & Water Conservation*, *49*(2 Suppl.). https://nrcca.cals.cornell.edu/soilFertilityCA/CA1/CA1_print.html

Brown, B., Westcott, M., Christensen, N., Pan, B., & Stark, J. (2005). Nitrogen Management for Hard Wheat Protein Enhancement. *Pacific Northwest Extension Publications*, *578*, 1–14.

Carlisle, L. (2015). *Lentil Underground*. Pengiun Random House LLC.

Carr, P. M., Martin, G. B., & Horsley, R. D. (2008). Wheat grain quality response to tillage and rotation with field pea. *Agronomy Journal*, *100*(6), 1594–1599. https://doi.org/10.2134/agronj2008.0122

Cotton, J., & Acosta-Martínez, V. (2018). Intensive Tillage Converting Grassland to Cropland Immediately Reduces Soil Microbial Community Size and Organic Carbon. *Ael*, *3*(1), 0. https://doi.org/10.2134/ael2018.09.0047

Cutforth, H. W., McGinn, S. M., McPhee, K. E., & Miller, P. R. (2007). Adaptation of pulse crops to the changing climate of the northern Great Plains. *Agronomy Journal*, *99*(6), 1684–1699. https://doi.org/10.2134/agronj2006.0310s

Derksen, D. A., Anderson, R. L., Blackshaw, R. E., & Maxwell, B. (2002). Weed dynamics and management strategies for cropping systems in the northern Great Plains. *Agronomy Journal*, *94*(2), 174–185. https://doi.org/10.2134/AGRONJ2002.1740

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

Dhuyvetter, K. C., Thompson, C. R., Norwood, C. A., & Halvorson, A. D. (1996b). Economies of dryland cropping systems in the Great Plains: A review. *Journal of Production Agriculture*, *9*(2), 216–222. https://doi.org/10.2134/jpa1996.0216

FSA Crop Acerage Data. (2022). https://www.fsa.usda.gov/news-room/efoia/electronic-reading-room/frequently-requested-information/crop-acreage-data/index

Gan, Y. T., Miller, P. R., McConkey, B. G., Zentner, R. P., Stevenson, F. C., & McDonald, C. L. (2003). Influence of diverse cropping sequences on durum wheat yield and protein in the semiarid northern Great Plains. *Agronomy Journal*, *95*(2), 245–252. https://doi.org/10.2134/agronj2003.0245

Govaerts, B., Mezzalama, M., Unno, Y., Sayre, K. D., Luna-Guido, M., Vanherck, K., Dendooven, L., & Deckers, J. (2007). Influence of tillage, residue management, and crop rotation on soil microbial biomass and catabolic diversity. *Applied Soil Ecology*, *37*(1–2), 18–30. https://doi.org/10.1016/j.apsoil.2007.03.006

Hansen, N. C., Allen, B. L., Baumhardt, R. L., & Lyon, D. J. (2012). Research achievements and adoption of no-till, dryland cropping in the semi-arid U.S. Great Plains. *Field Crops Research*, *132*, 196–203. https://doi.org/10.1016/j.fcr.2012.02.021

Havlin, J. L., Kissel, D. E., Maddux, L. D., Claassen, M. M., & Long, J. H. (1990). Crop rotation and tillage effects on soil organic carbon and nitrogen. *Soil Science Society of America Journal*, *54*(2), 448–452. https://doi.org/10.2136/sssaj1990.03615995005400020026x

Holford, I. C. R., Doyle, A. D., & Leckie, C. C. (1992). Nitrogen response characteristics of wheat protein in relation to yield responses and their interactions with phosphorus. *Australian Journal of Agricultural Research*, *43*(5), 969–986. https://doi.org/10.1071/AR9920969

Holtzer, T. o., Anderson, R. L., McMullen, M. P., & Peairs, F. B. (1996). Integrated Pest Management of Insects, Plant Pathogens, and Weeds in Dryland Cropping Systems of the Great Plains. *Jpa*, *9*(2), 200. https://doi.org/10.2134/jpa1996.0200

Joshi, P. K., & Rao, P. P. (2017). Global pulses scenario: status and outlook. *Annals of the New York Academy of Sciences*, *1392*(1), 6–17. https://doi.org/10.1111/nyas.13298

Koeshall, S. T., Easterly, A. C., Werle, R., Stepanovic, S. V., & Creech, C. F. (2020). Planting date and seeding rate of field pea in the semi-arid high plains of Nebraska. *Agronomy Journal*, *November 2020*, 1–15. https://doi.org/10.1002/agj2.20535

Krupinsky, J. M., Tanaka, D. L., Merrill, S. D., Liebig, M. A., & Hanson, J. D. (2006). Crop sequence effects of 10 crops in the northern Great Plains. *Agricultural Systems*, *88*(2–3), 227–254. https://doi.org/10.1016/j.agsy.2005.03.011

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest Package: Tests in Linear Mixed Effects Models . In *Journal of Statistical Software* (Vol. 82, Issue 13, pp. 1–26). https://doi.org/10.18637/jss.v082.i13

Lenssen, A. W., Johnson, G. D., & Carlson, G. R. (2007a). Cropping sequence and tillage system influences annual crop production and water use in semiarid Montana, USA. *Field Crops Research*, *100*(1), 32–43. https://doi.org/10.1016/j.fcr.2006.05.004

Lenssen, A. W., Johnson, G. D., & Carlson, G. R. (2007b). Cropping sequence and tillage system influences annual crop production and water use in semiarid Montana, USA. *Field Crops Research*, *100*(1), 32–43. https://doi.org/10.1016/j.fcr.2006.05.004

Lupwayi, N. Z., Rice, W. A., & Clayton, G. W. (1998). Soil microbial diversity and community structure under wheat as influenced by tillage and crop rotation. *Soil Biology and Biochemistry*, *30*(13), 1733–1741. https://doi.org/10.1016/S0038-0717(98)00025-X

Lupwayi, N. Z., & Soon, Y. K. (2009). Nitrogen release from field pea residues and soil inorganic N in a pea wheat crop rotation in northwestern Canada. *Canadian Journal of Plant Science*, *89*(2), 239–246. https://doi.org/10.4141/CJPS08019

Lupwayi, Newton Z., Lafond, G. P., May, W. E., Holzapfel, C. B., & Lemke, R. L. (2012). Intensification of field pea production: Impact on soil microbiology. *Agronomy Journal*, *104*(4), 1189–1196. https://doi.org/10.2134/agronj2012.0046

Miller, P., Bekkerman, A., Jones, C. A., Burgess, M. H., Holmes, J. A., & Engel, R. E. (2015). Pea in rotation with wheat reduced uncertainty of economic returns in southwest Montana. *Agronomy Journal*, *107*(2), 541–550. https://doi.org/10.2134/agronj14.0185

Miller, P. R., Engel, R. E., & Holmes, J. A. (2006). Cropping sequence effect of pea and pea management on spring wheat in the northern Great Plains. *Agronomy Journal*, *98*(6), 1610–1619. https://doi.org/10.2134/agronj2005.0302

Miller, P. R., Gan, Y., McConkey, B. G., & McDonald, C. L. (2003). Pulse crops for the northern Great Plains: I. Grain productivity and residual effects on soil water and nitrogen. *Agronomy Journal*, *95*(4), 972–979. https://doi.org/10.1177/0959683608098962

Miller, P. R., Waddington, J., McDonald, C. L., & Derksen, D. A. (2002). Cropping sequence affects wheat productivity on the semiarid northern Great Plains. *Canadian Journal of Plant Science*, *82*(2), 307–318. https://doi.org/10.4141/P01-116

Miller, Perry R., Bekkerman, A., Jones, C. A., Burgess, M. H., Holmes, J. A., & Engel, R. E. (2015). Pea in rotation with wheat reduced uncertainty of economic returns in southwest Montana. *Agronomy Journal*, *107*(2), 541–550. https://doi.org/10.2134/agronj14.0185

Miller, Perry R., McConkey, B. G., Clayton, G. W., Brandt, S. A., Staricka, J. A., Johnston, A. M., Lafond, G. P., Schatz, B. G., Baltensperger, D. D., & Neill, K. E. (2002). Pulse crop adaptation in the northern Great Plains. *Agronomy Journal*, *94*(2), 261–272. https://doi.org/10.2134/agronj2002.0261

Nielsen, D. C. (2001). Production functions for chickpea, field pea, and lentil in the central great plains. *Agronomy Journal*, *93*(3), 563–569. https://doi.org/10.2134/agronj2001.933563x

Nielsen, David C., Lyon, D. J., Hergert, G. W., Higgins, R. K., & Holman, J. D. (2015). Cover crop biomass production and water use in the Central Great Plains. *Agronomy Journal*, *107*(6), 2047–2058. https://doi.org/10.2134/agronj15.0186

Nielsen, David C., Unger, P. W., & Miller, P. R. (2005). Efficient water use in dryland cropping systems in the Great Plains. *Agronomy Journal*, *97*(2), 364–372. https://doi.org/10.2134/agronj2005.0364

Nielsen, David C., & Vigil, M. F. (2010a). Precipitation storage efficiency during fallow in wheat-fallow systems. *Agronomy Journal*, *102*(2), 537–543. https://doi.org/10.2134/agronj2009.0348

Nielsen, David C., & Vigil, M. F. (2017a). Intensifying a semi-arid dryland crop rotation by replacing fallow with pea. *Agricultural Water Management*, *186*, 127–138. https://doi.org/10.1016/j.agwat.2017.03.003

Nielsen, David C., & Vigil, M. F. (2018a). Soil water extraction for several dryland crops. *Agronomy Journal*, *110*(6), 2447–2455. https://doi.org/10.2134/agronj2018.05.0335

Nielsen, David C., & Vigil, M. F. (2018b). Wheat yield and yield stability of eight dryland crop rotations. *Agronomy Journal*, *110*(2), 594–601. https://doi.org/10.2134/agronj2017.07.0407

Nielsen, David C., Vigil, M. F., & Benjamin, J. G. (2011). Evaluating decision rules for dryland rotation crop selection. *Field Crops Research*, *120*(2), 254–261.

https://doi.org/10.1016/j.fcr.2010.10.011

Oelke, E., Oplinger, E., & Hanson, C. (1991). *Dry field pea*. Alternative Crops Manual. …. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Dry+Field+Pea#2

Pavek, P. L. S. (2012). Plant Guide for pea (Pisum sativum L.). *USDA-Natural Resources Conservation Service, Pullman, WA.*, 1–6. https://plants.usda.gov/plantguide/pdf/pg_pisa6.pdf

Peairs, F. B., Bean, B., & Gossen, B. D. (2005). Pest management implications of reduced fallow periods in dryland cropping systems in the Great Plains. *Agronomy Journal*, *97*(2), 373–377. https://doi.org/10.2134/agronj2005.0373

Peoples, M. B., Brockwell, J., Herridge, D. F., Rochester, I. J., Alves, B. J. R., Urquiaga, S., Boddey, R. M., Dakora, F. D., Bhattarai, S., Maskey, S. L., Sampet, C., Rerkasem, B., Khan, D. F., Hauggaard-Nielsen, H., & Jensen, E. S. (2009). The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis*, *48*(1–3), 1–17. https://doi.org/10.1007/BF03179980

Peterson, G. A., & Westfall, D. G. (2004). Managing precipitation use in sustainable dryland agroecosystems. In *Annals of Applied Biology* (Vol. 144, Issue 2, pp. 127–138). https://doi.org/10.1111/j.1744-7348.2004.tb00326.x

Querard, J., Markus, T. Z., Plamont, M. A., Gauron, C., Wang, P., Espagne, A., Volovitch, M., Vriz, S., Croquette, V., Gautier, A., Saux, T. Le, & Jullien, L. (2015). Photoswitching kinetics and phase-sensitive detection add discriminative dimensions for selective fluorescence imaging. *Angewandte Chemie - International Edition*, *54*(9), 2633–2637. https://doi.org/10.1002/anie.201408985

Schatz, B., & Endres, G. (2009). Field pea production A-1166 (revised). *NDSU Extension Service*, *1166*(MARCH 2003), 1–8.

Schillinger, W. F. (2017). Winter Pea: Promising New Crop for Washington's Dryland Wheat-Fallow Region. *Frontiers in Ecology and Evolution*, *5*. https://doi.org/10.3389/fevo.2017.00043

Schlegel, A. J., Assefa, Y., Haag, L. A., Thompson, C. R., Holman, J. D., & Stone, L. R. (2017). Yield and soil water in three dryland wheat and grain sorghum rotations. *Agronomy Journal*, *109*(1), 227–238. https://doi.org/10.2134/agronj2016.07.0387

Smika, D. E. (1970). Summer Fallow for Dryland Winter Wheat in the Semiarid Great Plains1. *Agronomy Journal*, *62*(1), 15. https://doi.org/10.2134/agronj1970.00021962006200010005x

Smith, E. C., & Young, D. L. (2000). Requiem for summer fallow. *Choices*, *First Quater*, 24–25.

Smýkal, P., Aubert, G., Burstin, J., Coyne, C. J., Ellis, N. T. H., Flavell, A. J., Ford, R., Hýbl, M., Macas, J., Neumann, P., McPhee, K. E., Redden, R. J., Rubiales, D., Weller, J. L., & Warkentin, T. D. (2012). Pea (Pisum sativum L.) in the Genomic Era. *Agronomy*, *2*(4), 74–115. https://doi.org/10.3390/agronomy2020074

Stepanovic, S., Milander, J., Peterson, J., Burr, C., Rudnick, D., Adesemoye, T., Creech, C., Werle, R., & Santra, D. (2016). Replacing Summer Fallow with Grain-Type Field Peas :

Rotational Costs and Benefits. *UNL CropWatch*.

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

Stepanovic, S. V., & Koeshall, S. T. (n.d.). *Field Peas—A Guide to Herbicide Carryover And Herbicide Efficacy*. CropWatch. Retrieved February 13, 2019, from https://cropwatch.unl.edu/2018/field-peas-—-guide-herbicide-carryover-and-herbicide-efficacy

Stevenson, F. C., & Kessel, C. van. (1996). The nitrogen and non-nitrogen rotation benefits of pea to succeeding crops. *Canadian Journal of Plant Science*, *76*(4), 735–745. https://doi.org/10.4141/cjps96-126

Tanaka, D. L., & Aase, J. K. (1987). Fallow method influences on soil water and precipitation storage efficiency. *Soil and Tillage Research*, *9*(4), 307–316. https://doi.org/10.1016/0167-1987(87)90056-0

Tanaka, D. L., Krupinsky, J. M., Liebig, M. A., Merrill, S. D., Ries, R. E., Hendrickson, J. R., Johnson, H. A., & Hanson, J. D. (2002). Dynamic cropping systems: An adaptable approach to crop production in the Great Plains. In *Agronomy Journal* (Vol. 94, Issue 5, pp. 957–961). https://doi.org/10.2134/agronj2002.9570

USA Dry Pea & Lentil Council. (2008). USA Dry Pea, Lentil & Chickpea Production. *USA Dry Peas, Lentils & Chickpeas: Processing Information & Technical Manual*, 31–54. https://www.usapulses.org/core/files/usapulses/uploads/files/Chapter3.pdf

Van Rhoon, G., Kanis, B., Zandbergen, H., Nowak, P., Nijdam, W., Schuurman, J. G., & Levendag, P. (2004). Soil compaction in cropping systems A review of the nature, causes and possible solutions. *Soil & Tillage Research*, *54*(4), 367–371. https://doi.org/10.1016/j.still.2004.08.009

Vaughan, B., Westfall, D. G., & Barbarick, K. A. (1990). Nitrogen Rate and Timing Effects on Winter Wheat Grain Yield, Grain Protein, and Economics. *Journal of Production Agriculture*, *3*(3), 324–328. https://doi.org/10.2134/jpa1990.0324

Vos, J., & Van Der Putten, P. E. L. (2001). Field observations on nitrogen catch crops. III. Transfer of nitrogen to the succeeding main crop. *Plant and Soil*, *236*(2), 263–273. https://doi.org/10.1023/A:1012795020139

Walley, F. L., Clayton, G. W., Miller, P. R., Carr, P. M., & Lafond, G. P. (2007). Nitrogen economy of pulse crop production in the Northern Great Plains. *Agronomy Journal*, *99*(6), 1710–1718. https://doi.org/10.2134/agronj2006.0314s

Wang, Price, K. P., Rich, P. M., Wang, J., Price, K. P., & Spatial, P. M. R. (2010). *Spatial patterns of NDVI in response to precipitation and temperature in the central Great Plains*. *1161*. https://doi.org/10.1080/01431160010007033

Wang, Rich, P. M., Price, K. P., Rich, P. M., & Temporal, K. P. P. (2010). Temporal responses of NDVI to precipitation and temperature in the central Great Plains , USA. *International Journal of Remote Sensing*, *1161*. https://doi.org/10.1080/01431160210154812

Wright, S. F., & Anderson, R. L. (2000). Aggregate stability and glomalin in alternative crop rotations for the central Great Plains. *Biology and Fertility of Soils*, *31*(3–4), 249–253. https://doi.org/10.1007/s003740050653