3-1-2023

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Renewable Agriculture and Food Systems

cambridge.org/raf

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Research Paper

Cite this article: Ruis SJ, Stepanovic S, Blanco-Canqui H (2023). Intensifying a crop–fallow system: impacts on soil properties, crop yields, and economics. *Renewable Agriculture and Food Systems* **38**, e42, 1–10. https://doi.org/10.1017/S1742170523000133

Received: 11 August 2022
Revised: 16 December 2022
Accepted: 1 March 2023

Keywords:
corn; crop yields; economics; fallow; field pea; intensifying cropping systems; soil properties; winter wheat

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Abstract

Intensifying crop–fallow systems could address increased weed control costs, increased land or rental costs, reduced crop diversity, and degraded soil properties in water-limited environments. One strategy to intensify such systems could be the insertion of a short-season crop during fallow. But, how this strategy affects soils, crop production, and farm economics needs further research. Thus, we studied the impacts of replacing fallow in a winter wheat (*Triticum aestivum* L)–corn (*Zea mays* L.)–fallow system with a short-season spring crop [field pea (*Pisum sativum* L.)] on crop yields and economics from 2015 to 2019 and 5-yr cumulative effects on soil properties using an experiment in the west-central US Great Plains. After 5 yr, replacing fallow with field pea increased microbial biomass by 294 nmol g^{-1} and plant available water by 0.08 cm^3 cm^{-3}, and reduced bulk density by 0.1 g cm^{-3} and cone index by 0.73 MPa in the 0–5 cm depth. It had, however, no effect on other soil properties. Field pea yield averaged 2.24 Mg ha^{-1}. Field pea reduced subsequent crop yield by 15–25% in two of three crops compared with fallow. However, economic analysis showed replacing fallow with field pea may improve net income by \$144–303 ha^{-1}, although income across the 5 yr differed by \$65 ha^{-1} in favor of fallow. Replacing fallow in winter wheat–corn–fallow rotation with a short-season spring crop offers promise to improve some near-surface soil properties while increasing net economic return during fallow under the conditions of this study.

Introduction

In water-limited regions, use of no-till summer fallow is a common practice to conserve water in crop–fallow systems. However, research indicates use of fallow results in low precipitation storage (<40%) and negative impacts on soil properties (Nielsen and Vigil, 2010; Rosenzweig, Fonte and Schipanski, 2018; Peterson et al., 2020). In order to restore soil properties and resilience to climatic stressors in these water-limited regions, intensification of crop–fallow systems is cited as a potential solution (Rosenzweig, Fonte and Schipanski, 2018; Degani et al., 2019; Kelly et al., 2021; Nicoloso and Rice, 2021; Simon et al., 2022). The few recent studies have shown continuous cropping systems can improve soil properties (Rosenzweig, Fonte and Schipanski, 2018; Kelly et al., 2021; Simon et al., 2022). For example, they may increase microbial biomass, soil organic C concentration, mean weight diameter of water-stable aggregates, and reduce bulk density (Rosenzweig, Fonte and Schipanski, 2018; Kelly et al., 2021; Simon et al., 2022). The main challenge is how to diversify or intensify crop–fallow systems in water-limited regions while enhancing soil properties, minimizing negative impacts on yields of subsequent crops, and maintaining or increasing profitability.

One of the potential methods to intensify crop–fallow systems could be the use of cover crops (Holman et al., 2018; Acharya et al., 2022). In semiarid regions, cover crops can provide many services including accumulation of soil organic C, reduction of nitrate leaching potential, and improvement in soil biology (Thapa et al., 2021; Kelly et al., 2021; Blanco-Canqui et al., 2021). However, the concern with using cover crops in water-limited regions is that they use water intended for the following crop and can thus reduce subsequent crop yield (Nielsen et al., 2016; Acharya et al., 2022). A study in northeastern Colorado found that cover crops reduced water content in five of eight site-years by 8.8% and winter wheat yield in four of eight site-years by 29.5% (Nielsen et al., 2016). Also, a study in southwest Kansas reported cover crops reduced water content by 47% and winter wheat yield by 11% (Holman et al., 2018).

A potential alternative to cover crops for intensifying crop–fallow can be planting a short-season crop such as field peas. The short-season crop still uses water, similar to cover crops, but be harvested for grain and generate income while providing additional biomass input to soil. Field peas are a relatively common short-season crop with over 8.1 million ha harvested worldwide in 2017 (Powers and Thavarajah, 2019). In the USA, about 0.81 million ha of field peas were harvested in 2018, 1.05 million in 2019, and 0.97 million in 2020 (USDA-NASS, 2018). Field peas and other leguminous crops have many benefits. Some benefits include breaking disease and weed cycles and adding N through N fixation (Powers and Thavarajah, 2019).

Table 1. Mean monthly temperature and precipitation for the experimental site near Enders, NE

	Temperature (°C)					Precipitation (mm)				
Month	2015	2016	2017	2018	2019	2015	2016	2017	2018	2019
Jan	−1.61	−1.36	−3.54	−3.28	−1.46	5.49	6.71	29.10	23.46	5.07
Feb	−0.79	1.95	2.76	−4.07	−6.88	7.89	30.39	5.29	19.53	6.39
Mar	7.65	6.34	6.93	4.34	1.10	2.80	20.77	62.36	25.93	45.45
Apr	10.23	9.36	10.15	6.67	9.50	62.75	143.59	55.39	31.01	32.82
May	13.42	13.87	14.29	17.52	12.03	254.00	100.09	101.36	111.75	115.81
Jun	21.99	22.89	21.71	22.47	20.13	47.46	79.17	11.37	61.78	135.06
Jul	23.64	24.19	25.06	23.45	23.92	14.81	58.01	39.74	122.03	117.16
Aug	22.30	21.76	20.96	21.42	22.47	65.54	50.95	72.72	37.23	81.67
Sep	20.40	18.25	18.11	18.46	20.30	25.44	90.06	75.99	21.33	30.51
Oct	12.42	13.05	9.97	8.00	6.10	63.36	12.39	10.82	78.10	9.84
Nov	2.61	6.10	4.94	1.24	2.25	35.91	8.19	4.67	39.53	18.85
Dec	−1.10	−3.83	−2.58	−1.65	0.32	9.30	18.17	2.98	15.68	12.80
Total						589	612	443	564	606

Despite the significant proportion of land area under field peas, little research on the impacts of field pea and other short-season crops on soil properties exists. The few previous studies on field pea mainly focused on soil organic C, N, and microbial activity (Lupwayi et al., 2012; O'dea et al., 2015; Morrow et al., 2016; Liu et al., 2020). One of these previous studies found no effect of field pea on soil organic C concentration in Oregon (Morrow et al., 2016). Others reported field pea had mixed effects on soil N fractions, depending on sampling time, previous crop, year, and other factors (Stevenson and Van Kessel, 1996; Miller, Engel and Holmes, 2006; Lupwayi and Soon, 2009; Sainju et al., 2017; Liu et al., 2020).

Data on how replacing fallow with short-season crops affects subsequent crop yields and farm economics are also scant (Miller et al., 2015; Nielsen and Vigil, 2017; Khakbazan et al., 2020). Nielsen and Vigil (2017) suggested the use of field pea as a fallow replacement may lead to yield reduction of a subsequent crop, especially if the soil water profile is not replenished during the off-season. Despite the reduction in subsequent crop yields in some years, the economics of rotations with field pea may be similar to or better than fallow (Miller et al., 2015; Ostmeyer, 2019; Khakbazan et al., 2020). While the few previous studies show potential for the use of field pea as an alternative to fallow, additional research is needed to assess the impacts of short-season crops on soil properties, crop yields, and farm economics. Thus, we studied the impacts of replacing fallow in a winter wheat–corn–fallow rotation with a short-season spring crop (field pea) on crop yields and economics for 5 years from 2015 to 2019 and 5-yr cumulative effects on soil properties using an experiment in the west-central US Great Plains.

Materials and methods

Site description, experimental design, and field management

To accomplish our objective, we established a field experiment near Enders, NE (40.378936 N; −101.539921 E) in 2015. The soil was a Blackwood loam (fine-silty, mixed, superactive, mesic Pachic Haplustolls) with 17 $g\,kg^{-1}$ organic matter in the 0–20 cm depth in 2015. The long-term mean annual temperature was 9.5°C and mean annual precipitation was 502 mm while monthly temperature and precipitaiton amounts are given in Table 1. Prior to this experiment, the field had been managed under no-till winter wheat–corn–fallow. In 2015, to establish the present experiment, the field was divided into strips of field pea and fallow. The field was under corn in 2014 (year prior to experiment start). The experimental design was a randomized complete block with two treatments (fallow and field pea) prior to winter wheat with 10 replications in a rainfed no-till winter wheat–corn–fallow. Thus, plots designated as fallow had the following cropping sequence from 2015 to 2019: fallow–winter wheat–corn–fallow–winter wheat while the field pea plots were: field pea–winter wheat–corn–field pea–winter wheat for the same time. The plot size was 18.3 m wide by 792.5 m long.

Table 2 summarizes field activities and seeding and fertilization rates. Field peas were planted late March in 2015 and 2018 and harvested the following July. Note that because of the rotation, each crop was not planted every year. Field peas were inoculated with N-fixing bacteria and a starter fertilizer was applied at planting as indicated in Table 2. The fallow treatment plots were kept weed-free using herbicide application. Winter wheat was planted in late September of 2015 and 2018 and harvested in July the following year (2016 and 2019). Corn was planted across the whole study area in 2017, which bridged the two field pea–winter wheat cycles. Winter wheat and corn were fertilized as indicated in Table 2.

Soil sampling and analysis

In this study, to assess how a short-season crop affected soil properties, we measured changes in soil microbial biomass, soil chemical properties of pH and concentrations of total organic matter, and nutrients, and soil physical properties of compaction (bulk density and cone index), water infiltration and retention, and wet and dry aggregate stability. All soil sampling and field soil measurements occurred in October 2019, three months after winter wheat harvest. Due to the large plot size, all measurements and soil sampling occurred within a 12 m diameter area at the north end of the plot.

Table 2. Field management for the 5-yr experiment of replacing fallow with field pea in a winter wheat–corn-fallow rotation near Enders, NE

Date	Management
2015	
27 Mar	Planted field peas inoculated with Cell-tech dry and liquid inoculant Applied starter fertilizer (8-24-0) at 94.6 L ha^{-1}
20 Jul	Harvested field peas
26 Aug	Fertilized with dry urea (42-0-0) at 56.8 kg ha^{-1} Applied starter fertilizer (10-34-0) at 28.4 L ha^{-1}
28 Sep	Planted winter wheat
2016	
15 Jul	Harvested winter wheat
2017	
4 May	Fertilized with 32-0-0 at 125 kg ha^{-1} Planted corn Applied starter fertilizer (10-34-0) at 47.3 L ha^{-1}
25 Oct	Harvested corn
2018	
21 Mar	Planted field peas inoculated with Cell-tech dry and liquid inoculant
20 Jul	Harvested field peas
30 Aug	Fertilized with dry urea (42-0-0) at 56.8 kg ha^{-1} Applied starter fertilizer (10-34-0) at 28.4 L ha^{-1}
21 Sep	Planted winter wheat
2019	
22 Jul	Harvested winter wheat
17 Oct	Collected soil samples and conducted field measurements

Penetration resistance was measured using a hand penetrometer (Eijkelkamp Co., Giesbeek, the Netherlands; Lowery and Morrison, 2002) at ten locations per plot for the 0–5 and 5–10 cm depth intervals. The penetration resistance value was converted to cone index using the basal area of the cone. Also, soil water content was determined using intact soil cores (Grossman and Reinsch, 2002), as explained later, to study potential correlations between penetration resistance values and soil water content.

We assessed water infiltration using a double ring infiltrometer with the falling head method (Reynolds et al., 2002). The double rings (75 cm outer ring and 25 cm inner ring) were placed in non-trafficked areas of the plot. The water level of the inner ring was recorded at times of 0, 1, 2, 3, 4, 5, 10, 30, 60, 90, 120, 150, and 180 min after addition of water. The 180 min reading was assumed to be steady-state infiltration rate. We calculated the infiltration rate and cumulative infiltration at each measurement interval.

Bulk soil samples were collected from the 0 to 5 and 5 to 10 cm depth intervals with a flat-bottom shovel. The bulk soil samples were used for the analysis of dry- and wet-aggregate stability and concentrations of organic matter, and nutrients. Half of the bulk sample was allocated for dry-aggregate stability. We measured soil dry-aggregate stability using the methods of Nimmo and Perkins (2002). About 1000 g of air-dried soil sample were placed on a stack of sieves with openings of 44, 14, 6.3, 2, 0.84, 0.43, and <0.42 mm in a RoTap sieve shaker (W.S. Tyler, Mentor, OH, USA). The samples were sieved for 5 min and the mass of aggregates on each sieve determined to compute wind erodible fraction (soil aggregates <0.84 mm) and geometric mean diameter of dry aggregates (Nimmo and Perkins, 2002).

Wet aggregate stability was measured on 50 g of air-dry soil passed through 8 mm sieves. The 50-g sample was saturated for 10 min through capillary action on a filter paper placed on a stack of nested sieves with openings of 4.75, 2, 1, 0.5, and 0.25 mm. The sieve stack was mechanically sieved in water for 10 min. The mass of aggregates retained on each sieve was dried at 105°C for 48 h and weighed. Each aggregate fraction was corrected for sand content by sieving the sample through a 0.53 µm sieve, drying at 105°C for 24 h, and weighing. The mean weight diameter of sand-free water-stable aggregates was then calculated (Nimmo and Perkins, 2002).

The concentration of soil C was assessed using the dry combustion method (Nelson and Sommers, 1996) and concentration of organic matter by loss on ignition (Combs and Nathan, 2015). The soil pH was determined by the methods of Peters, Nathan and Laboski (2015) and electrical conductivity by the methods of Whitney (2015) using the 1:1 soil water method with pH and electrical conductivity meters. Nitrate-N was determined using the cadmium reduction technique (Gelderman and Beegle, 2015), P concentration using colorimetric measurement of Bray extracts (Frank, Beegle and Denning, 2015), and the concentrations of Ca, Mg, Na, and cation exchange capacity (CEC) using atomic absorption emission spectroscopy of Mehlich III extractions (Warncke and Brown, 2015).

Total microbial biomass (phospholipid fatty acid analysis) was determined on air-dried samples sieved through 2 mm and analyzed using the methods of Hamel et al. (2006). The microbial groups based on the fatty acids were: bacteria (19:0 iso, 19:0 anteiso, 14:0 iso, 15:0, 15:0 iso, 15:0 anteiso, 16:0 iso, 17:0, 17:0 iso, 17:0 anteiso,10:0 2OH, 10:0 3OH, 11:0 2OH, 11:0 3OH, 11:0 iso 3OH, 12:2 OH, 12:0 3OH, 13:0 iso 3OH, 14:0 2OH, 14:0 3OH, 15:0 anteiso, 16:0 iso, 16:1 ω7c, 16:1 ω7t, 16:1 ω9c; 16:0 2OH, 16:0 3OH, 16:1 2OH, 17:0 cyclo, 18:1 ω5c, 181 ω7c, 19:0 cyclo ω9, 19:0 cyclo ω9c, 19:0 cyclo ω6), and fungi (16:1 ω5c, 16:1 ω11c, 20:1 9c, 22:1 ω3c, 18:1 ω9c, 18:2 ω6, 9c, 18:2 ω6c, 18:3 ω3c, 18:3 ω6c, 18:3 ω6c 6, 9, 12).

To determine bulk density, field gravimetric water content, and water retention, we collected two intact 5 × 5 cm soil cores from each plot for the 0–5 and 5–10 cm depth intervals. The cores were inserted into the soil using a slide hammer until the cores were completely full with soil. The cores were placed in plastic bags to avoid moisture loss and stored at 2.2°C until processing. To determine field gravimetric water content and water retention, the intact soil cores were carefully trimmed flush with the metal core and weighed. Field gravimetric water content was computed by weighing the soil cores before water retention measurements and determining the oven drying at 105°C for 24 h at the end of water retention measurement at −33 kPa matric potential (Grossman and Reinsch, 2002).

Water retention was determined at −33 (field capacity) and 1500 kPa (permanent wilting point) matric potentials. The intact soil cores were attached with cheesecloth and rubber band at the bottom to hold the soil in the core and slowly saturated from the bottom by capillary action over 24 h. The saturated soil cores were placed in a low-suction pressure extractor and drained at −33 kPa matric potential until equilibrium was reached in about 5 d (Klute, 1986). Next, the soil core was weighed and a subsample was extracted from the core and dried at 105°C for 24 h to determine gravimetric water content, bulk density using the core method, and then volumetric water content at −33 kPa matric potential (Grossman and Reinsch, 2002). The rest of soil in the core was then air-dried and ground to pass a 2-mm sieve. The sieved sample was re-packed into 1 × 5 cm rings on a −1500 kPa ceramic plate, allowed to saturate for 24 h, placed on a high-pressure extractor, and then drained at −1500 kPa matric potential till drainage ceased. Then, the soil sample was weighed, dried at 105°C for 24 h, and weighed again to determine volumetric water content at −1500 kPa matric potential (Klute, 1986). Plant available water was computed as the difference in volumetric water content between −33 and −1500 kPa matric potential.

Determination of crop yields and economic analysis

Field pea, winter wheat, and corn were mechanically harvested from each plot with yields from each plot quantified using a weigh wagon. The average moisture contents were 12.1% for field peas in 2015, 12.8% for wheat in 2016, 15.1% for corn in 2017, 12.6% for field peas in 2018, and 11.6% for wheat in 2019. To investigate the impacts of field pea *vs* fallow on net income, we evaluated expenses *vs* income. We recorded seed, fertilizer, inoculant, and herbicide rates on a per ha basis. The costs of each seed type, fertilizer type, inoculant, and herbicide were collected from the Nebraska Crop Budgets (Klein, Wilson and Johnson, 2015, 2016, 2017, 2018; Klein, McClure and Wilson, 2019). The costs were scaled based on the actual application or seeding rates. We then included rates for planting, spraying, and harvesting based on the Nebraska Crop Budgets. We used the Nebraska Crop Budget values for these field operations and costs since this is a Nebraska-based study. The costs of field operations given the Nebraska Crop Budgets include labor, fuel and lube, and repairs and ownership costs. Note that the Nebraska Crop Budgets are compiled each year to reflect changes in product costs and labor and fuel rates, hence the cost of a particular field operation or item may vary among years. The value of each grain crop ($ Mg^{-1}) was determined from the values reported by USDA (USDA, 2017, 2019, 2020). The grain values were then multiplied by the total yields on a per ha basis. We did not assign values to changes in soil properties.

Statistical analysis

Soil property data (soil microbial biomass, soil chemical properties of pH and concentrations of total organic matter, and nutrients, and soil physical properties of bulk density, cone index, water infiltration and retention, and wet and dry aggregate stability) were analyzed by the PROC GLIMMIX procedure in SAS by soil depth (except water infiltration) for a randomized complete block design (SAS Institute, 2021). Crop yields were assessed by year. The treatments (fallow and field pea) were the fixed effects and replication the random factor. Data were normally distributed as per the PROC UNIVARIATE test in SAS. Means between the two treatments were compared using LSMEANS in PROC GLIMMIX. The PROC CORR procedure was used to study relationships among the various soil properties. Means and correlations were considered significant at $P < 0.05$.

Results

Soil properties

Replacing fallow with field pea had a significant impact on soil microbial biomass, bulk density, cone index, volumetric water content at −33 kPa (field capacity), and plant available water, but had no effect on other soil properties (Tables 3–5). Field pea increased microbial biomass by 104% (284 *vs* 578 nmol g^{-1}) and bacteria biomass by 85% (53 *vs* 98 nmol g^{-1}) compared with fallow but only in the upper 5 cm soil depth (Table 3). Fungi biomass was unaffected by fallow replacement with field pea. As shown in Table 4, no chemical property, including soil organic matter, was affected by replacing fallow with field pea.

Table 3. Five-year cumulative impacts of replacing fallow with field pea on soil biological properties (mean ± SD) in a winter wheat–corn–fallow rotation at a site near Enders, NE

Treatment	Total microbial biomass	Total bacteria	Total fungi
	nmol g^{-1}		
0–5 cm depth			
Fallow	283.7 ± 153.7b	53.1 ± 18.6b	2.3 ± 2.3
Fallow replaced	578.0 ± 241.9a	98.0 ± 29.9a	13.6 ± 19.4
5–10 cm depth			
Fallow	95.0 ± 85.4	12.1 ± 15.1	0 ± 0
Fallow replaced	189.9 ± 194.6	31.2 ± 35.5	5.8 ± 10.8

Different lowercase letters within a column and soil sampling depth are statistically significant at $P < 0.05$.

Field pea reduced soil compaction parameters of soil bulk density by 8% (1.3 *vs* 1.2 g cm^{-3}) and cone index by 38% (1.9 *vs* 1.2 MPa) compared with fallow at the 0–5 cm depth (Table 5). Cone index was not significantly correlated with water content ($r = 0.27$; $P = 0.45$), which was unaffected by fallow replacement with field pea. Thus, cone index values were not adjusted for differences in water content (Busscher et al., 1997; Blanco-Canqui et al., 2005). Replacing fallow with field pea did not affect geometric mean diameter of dry aggregates nor the wind erodible fraction (aggregates <0.84 mm). Field pea also did not affect mean weight diameter of water-stable aggregates relative to fallow. Replacing fallow with field pea improved volumetric water content at −33 kPa (field capacity); but not volumetric water content at −1500 kPa (permanent wilting point) nor water infiltration rate. Compared with fallow, field pea increased volumetric water content at field capacity by 39% (0.23 *vs* 0.32 $\mathrm{cm}^3\ \mathrm{cm}^{-3}$), and plant available water by 57% (0.14 *vs* 0.22 $\mathrm{cm}^3\ \mathrm{cm}^{-3}$). At the 5–10 cm depth, field pea had no effect on any soil physical property compared with fallow. Correlation analysis showed few relevant correlations among soil properties (data not shown). Soil bulk density was negatively correlated with mean weight diameter of water-stable aggregates ($r = -0.68$; $P < 0.05$).

Crop yields and economics

Field pea affected subsequent grain yield in two of three years. Because of the rotation cycle, which was field pea (in place of fallow)–winter wheat–corn, field pea was grown in years 1 and 4, winter wheat in years 2 and 5, and corn in year 3. Field pea yields were 2.45 Mg ha^{-1} in year 1 (2015) and 2.04 Mg ha^{-1} in year 4 (2018) (Fig. 1). Replacing fallow with field pea reduced winter wheat yield in year 2 (2016) by 25% and corn yield in year 3 (2017) by 15%. Field pea did not reduce winter wheat yield in year 5 (2019) compared with fallow. Field peas added \$419–\$616 ha^{-1} of income during the fallow year; however,

Table 4. Five-year cumulative impacts of replacing fallow with field pea on soil chemical properties (mean ± S.D.) in a winter wheat–corn–fallow rotation at a site near Enders, NE

Treatment	pH	Electrical conductivity	Organic matter	Soil organic C	NO$_3$	P	K	Ca	Mg	Na	CEC
		(dS m^{-1})	(g kg^{-1})	(g kg^{-1})	(mg kg^{-1})						
0–5 cm depth											
Fallow	5.14 ± 0.08	0.25 ± 0.02	20.2 ± 0.75	11.6 ± 1.7	22.7 ± 1.04	68.8 ± 10.5	565 ± 33.9	843 ± 88.6	155 ± 15.2	14.0 ± 8.02	14.3 ± 1.03
Fallow replaced	5.24 ± 0.12	0.27 ± 0.03	22.0 ± 1.55	11.7 ± 2.3	23.9 ± 6.11	67.4 ± 6.40	550 ± 40.17	865 ± 71.0	149 ± 12.3	10.6 ± 1.35	13.2 ± 0.83
5–10 cm depth											
Fallow	5.22 ± 0.07	0.13 ± 0.01	17.0 ± 1.09	8.2 ± 0.5	7.18 ± 1.21	57.6 ± 17.9	498 ± 76.7	1081 ± 87.5	182 ± 11.5a	9.40 ± 1.36	15.5 ± 1.67
Fallow replaced	5.26 ± 0.08	0.14 ± 0.01	17.2 ± 1.17	8.6 ± 00.8	7.72 ± 0.86	48.0 ± 7.46	486 ± 54.1	1092 ± 62.3	173 ± 8.79b	8.80 ± 0.98	15.1 ± 0.60

Different lowercase letters within a column and soil sampling depth are statistically significant at $P < 0.05$.

after expenses, the net income ranged from –\$17 to \$147 ha^{-1} (Table 6). In subsequent years, net income from wheat ranged from \$173 to \$442 ha^{-1} after fallow and –\$5 to \$323 ha^{-1} after field pea. Net income from corn was \$780 ha^{-1} after field pea and \$994 ha^{-1} after fallow. The cumulative net income across the 5 yr favored fallow over field pea, with a loss of \$27 ha^{-1}.

Discussion

Soil properties

Results indicate that replacing fallow in crop–crop–fallow systems with a short-season crop (field pea) can improve some soil properties after 5 yr although the improvement was mostly confined to the surface 5 cm of the soil. The positive soil effects, while few, of replacing fallow with short-season crop is promising and support the notion that intensifying cropping systems can result in improved soil conditions in semiarid environments (Rosenzweig, Fonte and Schipanski, 2018; Peterson et al., 2020). For example, while the extent of increase in plant available water was small (0.14 *vs* 0.22 cm^3 cm^{-3}), the increase was significant for this soil property, which is key to manage soil water storage in semi-arid environments.

The increase in microbial biomass suggests replacing fallow with a short-season legume crop increases microbial biomass. The increase in microbial biomass was probably driven by the influx of easily degradable legume residue from pea and tendency for increased soil organic matter. For example, legumes are well-known to have lower C:N ratios (29:1) than corn (57:1) or winter wheat (80:1) residues (USDA-NRCS, 2011). Thus, the influx of a readily degradable food source stimulated microbial activity despite field pea only occurring every third year.

We expected field pea would increase soil organic matter concentration due to the addition of crop residues during the fallow period, but this did not occur. Based on the crop yields (Fig. 1) and a field pea harvest index of 0.43 (Nleya and Rickertsen, 2011), the amount of residue added by field peas ranged from 2.32 to 3.25 Mg ha^{-1} per year. This residue amount is equivalent to cover crop biomass production levels in the region (Nielsen et al., 2015; Ruis et al., 2017; Holman et al., 2018). However, the cover crops in these studies were added every 12–18 months rather than every 36 months, thus the influx of biomass on an annual basis would be larger from the cover crop than from the field pea in this study. Despite these levels of cover crop biomass, cover crops may not increase soil organic C for long periods after termination (Blanco-Canqui et al., 2013). Without a significant change in organic matter, we did not expect to observe large changes in soil structural quality as organic matter can be an important driver of soil aggregation. In this study, replacing fallow with field pea did not alter wind or water erosion potential as indicated by wet and dry aggregate size.

The reduction in soil bulk density and cone index suggests that intensifying crop–fallow rotation with a short-season crop can reduce risks of soil compaction. For instance, note the cone index under the fallow treatment was near the 2 MPa threshold that can affect the root growth (Unger and Kaspar, 1994; Lin, He and Chen, 2016). However, the replacement of fallow with field pea reduced cone index to 1.2 MPa, which is about half below the threshold level. Previous studies of intensified cropping systems (including cover crops) in the region showed variable effects on compaction parameters (Rosenzweig, Fonte and Schipanski, 2018; Kelly et al., 2021; Simon et al., 2022), but our study suggests adding a short-rotation crop could be beneficial for reducing near-surface soil compaction.

Replacing fallow with a short-season crop did not affect water infiltration in spite of improving other soil properties. Studies measuring water infiltration in semiarid intensified cropping systems are few. Blanco-Canqui, Stone and Stahlman (2010) found intensified cropping systems such as continuous winter wheat increased cumulative water infiltration relative to crop–fallow systems in the central US Great Plains after 33 yr. We suggest that because water infiltration is slower to change than other soil properties, a longer (>5 yr) period of time after fallow replacement with a short-rotation crop is probably needed to observe changes in water infiltration.

Our results suggest a short-rotation crop can have similar impacts on soil properties to cover crops. Cover crop studies of similar duration in the region where fallow was replaced also found significant changes in soil properties including soil organic C concentration, wet aggregate stability, bulk density, water infiltration, soil fertility, microbial biomass and community structure, and others (Blanco-Canqui et al., 2013; Ghimire et al., 2019; Thapa et al., 2021; Simon et al., 2022). The similarities in changes in soil properties between field pea and cover crops compared with fallow can be due to similar quantities of biomass produced by these crops in the fallow period in crop–fallow systems.

Crop yields

The reduction crop yield following field pea in two of three subsequent crops (Fig. 1) was probably due to lower rainfall amounts during the pea year. A previous study using field pea as a

Table 5. Five-year cumulative impacts of replacing fallow with field pea on soil physical properties (mean ± s.d.) in a winter wheat–corn–fallow rotation at a site near Enders, NE

Treatment	Bulk density	Cone index	Geometric mean diameter of dry soil aggregates	Erodible fraction (<0.84 mm aggregates)	Mean weight diameter of water-stable aggregates	Water content at −33 kPa	Water content at −1500 kPa	Plant available water	Water infiltration rate
	($Mg\ m^{-3}$)	(MPa)	(mm)	(%)	(mm)	($cm^3\ cm^{-3}$)	($cm^3\ cm^{-3}$)	($cm^3\ cm^{-3}$)	($cm\ min^{-1}$)
0–5 cm depth									
Fallow	1.31 ± 0.07a	1.94 ± 0.22a	0.10 ± 0.02	18.1 ± 1.21	0.92 ± 0.26	0.23 ± 0.09b	0.10 ± 0.01	0.14 ± 0.09b	2.75 ± 4.20
Fallow replaced	1.21 ± 0.10b	1.21 ± 0.17b	0.08 ± 0.01	17.70 ± 1.26	1.44 ± 0.49	0.32 ± 0.08a	0.10 ± 0.01	0.22 ± 0.09a	0.52 ± 0.58
5–10 cm depth									
Fallow	1.46 ± 0.08	2.52 ± 0.33	na	na	0.40 ± 0.12	0.24 ± 0.08	0.08 ± 0.16	0.18 ± 0.21	na
Fallow replaced	1.43 ± 0.07	1.97 ± 0.11	na	na	0.41 ± 0.10	0.24 ± 0.09	0.10 ± 0.04	0.15 ± 0.10	na

Different lowercase letters within a column and soil sampling depth are statistically significant at $p < 0.05$. na denotes not applicable as dry aggregate size, the erodible fraction, and water infiltration are not measured with depth.

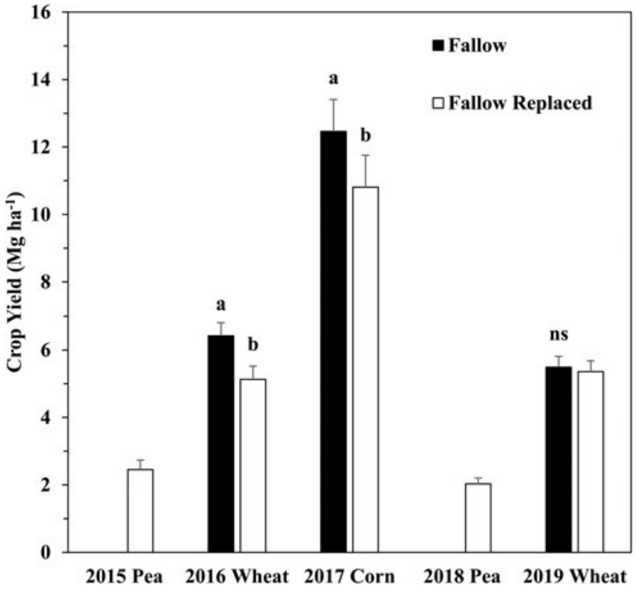

Figure 1. Impacts of replacing fallow with field pea on pea, winter wheat, and corn yield across 5 yr near Enders, NE. Note that fallow–winter wheat–corn treatment did not have a crop in 2015 and 2018, thus no yields were collected. Different lowercase letters above bars denote statistically different yields at $P < 0.05$. ns denotes non-significant. Error bars are standard deviation of the mean.

short-season crop to replace fallow reported that field pea can significantly reduce yields for the subsequent crop (Nielsen and Vigil, 2017). The lack of field pea effects on the third subsequent crop in our study was probably due to the overall wetter fall and spring periods. Note that field pea and winter wheat yields were higher than some studies in the region (Nielsen and Vigil, 2017; Liu et al., 2020). The overall higher crop yields in our study were likely due to the wetter climate than in previous studies. In addition, the annual precipitation across the 5-yr period was 12% higher than the long-term average which suggests replacing fallow with field pea may work the best in wetter years. However, the timeliness of rainfall coinciding with sowing time can be problematic is water-limited regions. Thus, there is risk of crop failure by adding a short-season crop if weather conditions are poor. Some have advocated the use of 'flex-rotations' where the crop to be planted changes depending on soil and predicted weather conditions (Blanco-Canqui et al., 2020). Our study suggests that flexibility in crop rotation may be warranted to take advantage of relatively wetter conditions in some years (i.e., based on long-term forecasts). The flexibility in crop rotation could lead to increased income from the crop used during fallow without negative impacts to yield when planted for appropriate conditions.

Economics

Results indicate that growing field pea could improve income during the fallow year as reported in Table 6, but not always as shown in 2018, particularly when pea is grown in drier years. The experimental data show that the income obtained by pea in 2015 is not sufficient to make the crop rotation scheme profitable over the 5 yr. If one evaluates the net income across the 5-yr experiment, economics differed by only \$27 ha^{-1}, that could be considered as not relevant losses when also looking at the potential value linked to ecosystem services that could be provided by this intensified cropping system.

Table 6. Expenses, grain income, credits, and net income under winter wheat (WW)-corn (C)-fallow with or without fallow replacement with field pea across 5 yr. Bold lettering denotes income differences between rotations.

Year and treatment	Crop	Insurance	Planting[a]	Seed	Inoculant	Pesticide	Pesticide application	Fertilizer	Fertilizer application	Harvest	Land rental	Total expenses	Grain income[b]	Annual net income	Cumulative net income
								($ ha^{-1})							
2015															
Fallow	Fallow					−39.35	−31.79				−111.15	−182.29		−182.29	−182.29
Fallow Replaced	Field Pea	−17.83	−40.43	−133.38	−19.76	−45.77	−21.07	−19.76		−60.17	−111.15	−469.32	616.00	146.68	146.68
Difference														**328.96**	**328.96**
2016															
Fallow	WW	−18.40	−40.43	−44.95		−100.90	−31.34	−262.56	−12.84	−59.40	−103.74	−674.58	847.44	172.86	−9.43
Fallow Replaced	WW	−26.03	−40.43	−44.95		−100.90	−31.34	−262.56	−12.84	−59.40	−103.74	−682.21	677.16	−5.05	141.62
Difference														**−177.91**	**151.05**
2017															
Fallow	C		−44.90	−85.34		−151.34	−21.19	−143.75	−13.09	−65.43	−96.33	621.38	1615.35	993.97	984.54
Fallow Replaced	C		−44.90	−85.34		−151.34	−21.19	−143.75	−13.09	−65.43	−96.33	621.38	1401.44	780.06	921.68
Difference														**−213.91**	**−62.86**
2018															
Fallow	Fallow					−48.17	−22.67				−101.27	−172.11		−172.11	812.43
Fallow Replaced	Field Pea	−17.83	−27.19	−146.72	−19.76	−48.56	−15.12			−59.50	−101.27	−435.96	418.69	−17.27	904.42
Difference														**−154.84**	**−91.99**
2019															
Fallow	WW	−18.40	−27.19	−36.93		−52.54	−30.23	−181.79	−12.94	−59.50	−93.86	−513.39	955.35	441.96	1254.40
Fallow Replaced	WW	−26.03	−27.19	−36.93		−52.54	−30.23	−181.79	−12.94	−59.50	−93.86	−521.02	844.40	323.38	1227.80
Difference														**−118.58**	**−26.60**

WW, winter wheat; C, corn.

[a] Planting, herbicide application, and fertilizer application include labor, fuel and lube, and repairs and ownership costs based on the Nebraska Crop Budgets (Klein, Wilson and Johnson, 2015, 2016, 2017, 2018; Klein, McClure and Wilson, 2019).

[b] Prices were \$251.43 Mg^{-1} for pea in 2015; \$132.00 Mg^{-1} for winter wheat in 2016; \$129.65 for corn in 2017; \$206.25 for pea in 2018; \$165 Mg^{-1} for winter wheat in 2019 and based on USDA crop values for that year.

Table 7. Review of field pea effects on farm economics.

Location	Crop rotation	Field pea phase net income	Net income across rotation (\$ ha^{-1})	Reference
Kansas, USA	Fallow–winter wheat–corn		−196	Ostmeyer (2019)
	Field pea–winter wheat–corn	−85	−175	
Montana, USA	Fallow–wheat		266	Miller et al. (2015)[a]
	Field pea–wheat	274	1761	
Kansas, USA	Fallow–winter wheat		−135	Holman et al. (2018)[b]
	Field pea–winter wheat	−169	−282	

[a] Calculated based on expenses and gross income given by Miller et al. (2015).

[b] Calculated based on total expenses of \$309 ha^{-1} and income of \$140 ha^{-1}.

Short-season crops such as field pea offer an opportunity to show more positive cash flow during what would be fallow years. If dollar values were placed on improvement in soil properties such as reduced bulk density (reduced soil compaction risks) and increased organic matter, nutrients, and water holding capacity, the net return could be higher under field pea than the estimates above. Assigning dollar values to soil property changes is, however, difficult and an area that deserves further consideration in future research (Pratt et al., 2014).

The few available studies evaluating economics in crop–fallow with field pea indicate field pea can have variable effects on economics (Table 7). For example, a study in northwest Kansas reported replacing fallow with field pea in a winter wheat–corn–fallow rotation resulted in only a small increase in net income (Ostmeyer, 2019; Table 7). A southwest Kansas study showed lower net incomes for field pea in a winter wheat–fallow rotation (Holman et al., 2018; Table 7). In a study in Montana, net incomes were higher for field pea than for fallow (Miller et al., 2015; Table 7). Our economic findings were similar to the Kansas studies and dissimilar from the Montana study. The differences between our study and the Montana study were higher seed, machinery, and labor costs for our study in addition to including the land costs.

Conclusion

This 5-yr study conducted in a water-limited environment in the west-central US Great Plains indicates that replacing fallow in crop–fallow systems with a short-season spring crop such as field pea can have positive effects on some soil properties. The intensification of the crop–fallow system can increase soil biological activity with accompanying reduction in compaction and increase in plant available water. However, the positive changes in soil properties were detectable only near the soil surface (0–5 cm depth). Results also indicate the addition of a short-season spring crop can reduce subsequent crop yields in some years, which is similar to the impacts of cover crops on subsequent crops in water-limited regions. Nevertheless, the economic analysis indicates replacing fallow with a short-season spring crop improves income during the fallow phase although negative impacts on cumulative net income do occur. Intensifying crop–fallow systems with a short-season crop appears to have an edge over the use of cover crops in terms of economics if they are not used for alternative uses (i.e., harvesting or grazing), but may have similar impacts on soil properties. Additional long-term data from multiple locations are needed to further corroborate the findings of this study. Overall, replacing fallow in winter wheat–corn–fallow rotation with a short-season spring crop offers promise to improve near-surface soil properties while increasing fallow economic return under the conditions of this study.

Acknowledgments. This material is based upon work that is supported by the National Institute of Food and Agriculture, US Department of Agriculture, under award no. 2016-38640-23781 through the North Central Region SARE program under project no. LNC16-385. USDA is an equal opportunity employer and service provider. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the US Department of Agriculture.

Competing interests. None.

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