THESIS

YIELD AND WATER USE EFFICIENCY OF WINTER PEAS PLANTED IN CEREAL RESIDUES

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In partial fulfillment of the requirements
For the Degree of Master of Science
Colorado State University
Fort Collins, Colorado
Fall 2025

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ABSTRACT

CEREAL RESIDUE EFFECTS ON WINTER PEAS

Sowing pulse crops into the residue of former cereal crops, such as winter wheat (*Triticum aestivum*), has been shown to provide numerous crop benefits. Straw left behind creates a favorable microhabitat for plant overwintering and water conservation by moderating soil temperature, diminishing the influence of solar radiation, and cutting potential evaporation during the summer growing season. This research project examined three hypotheses involving winter peas (*Pisum sativum* L.): i. Do winter peas planted no-till in standing cereal residue yield more kg ha^{-1} of edible grain than winter peas planted in disc harrowed cereal residue, ii. Do winter peas have higher water use efficiency (WUE) kg ha^{-1} mm^{-1} when planted in standing wheat and triticale residue versus winter peas planted in conventionally tilled cereal residue, and iii. Is it economically profitable to incorporate winter peas as part of a cereal-winter pea rotation in place of a continuous winter wheat rotation. Winter peas planted into standing cereal residue improved grain yield but did not significantly improve water use efficiency as compared to planting into soil prepared with a tandem disc harrow. Economic enterprise and partial budgets determined that a change to winter wheat-winter pea rotation versus continuous winter wheat produced a net economic loss.

ACKNOWLEDGEMENTS

The author would like to gratefully acknowledge the members of the committee and staff members of WCRC-GV that assisted in the project: Adam Bisker, Tye Blacklock, Jim Fry, Karmen Lillard, Michael Lobato.

DEDICATION

To my parents, for always supporting my love of the natural world.

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INTRODUCTION

Winter peas (*Pisum sativum* L.), a winter hardy form of dry peas, are gaining popularity as a rotational crop that may be more adaptable to changing climatic patterns. Historically, pulses such as dry peas have gained favor in the Northern Great Plains to enhance rotations involving wheat-fallow rotations that utilized no-till systems (Cutforth et al., 2007). In 2000, Montana harvested 8,400 ha of edible dry peas, and North Dakota 24,800 ha; by 2025, Montana harvested 232,000 ha of dry edible peas, and North Dakota 140,000 ha (USDA, 2025a). Research has found that alternating pulses and cereal crops with different rooting patterns and depths helps reduce water deficit, improving water use efficiency (Liu et al., 2011; Gan et al., 2003; Miller et al., 2003). Winter peas have long been known to fix atmospheric nitrogen (N) while reducing reliance on inorganic N fertilizer.

Dry peas act as a practical rotational component to prevent cereal disease and insect outbreaks and increase post-harvest residual soil water by leaving behind moisture below 30 cm (Neugschwandtner et al., 2020; Chen et al., 2006; Badaruddin and Meyer, 1994; Miller et al., 2002, 2003). Rotations of winter peas and cereals may create a more conducive environment for growth, resulting in higher crop yields and crop quality. Soil erosion is diminished by slowing wind speed, thereby reducing evaporation and improving both soil moisture and moderating air temperatures for dry peas to attain higher water use efficiency and yield (Cutforth et al., 2002). Miller et al. (2002) observed that wheat grown in pulse stubble had a greater yield than wheat planted into oilseed stubble or wheat on wheat residue, and grain protein content was higher in wheat sown into pulse stubble.

Winter peas, climate and cereal residue

Perhaps the greatest contribution of winter peas is their ability to adapt to and grow in shoulder seasons such as fall and spring where warmer, wetter temperatures due to climate change, have expanded the growing season (Trnka et al., 2011). The Fruita area of the Grand Valley of western Colorado (Lat 39.1830, Long 108.6970, elev. 1,403 m) has a long history of successfully producing high yielding agronomic row crops such as: sugar beets, field corn, winter wheat, and dry beans. The region has silty clay loam soils, a long, frost-free growing season ranging between 140-180 days with an average first hard freeze (< -1.8°C) of October 14th (NWS, 2025) and reliable irrigation water from the Colorado River from April-October.

Despite these attributes, long term drought and economic market factors have impacted farmers and limited crop rotations in the region. Local markets for producers have been limited and a steady decline in dry bean production acreage statewide has left many local crop rotations with no annual, life-cycle legume. The addition of an annual legume to a continuous wheat or corn-wheat rotation could help producers to reap the benefits of winter peas such as improved N credits and a viable high-quality forage or a high-protein grain for specialty food markets.

Climate Influence on Planting Date

Based on observations from three years of planting, fall and spring, growing and harvesting winter peas in silty clay loam soils, and the help of the proceeding five years of monthly mean, monthly minimum temperature records from the Colorado Coagmet FRT-03 weather station (https://coagmet.colostate.edu/cgi-bin/monthly_coag.pl), there appear to be two primary growing seasons suited for dry peas: fall-planted and spring-planted.

Fall and spring seasons both end in July and are primarily differentiated by their planting date, and whether they have successfully overwintered. Winter peas planted in September and October are exposed to a combination of moderate air and soil temperatures that likely foster germination, emergence and quick vegetative growth. Looking at the most recent complete five-year average daily air and soil temperatures, and precipitation for September and October for the period 2020-2024, there are some subtle yet consequential differences for producing winter peas (Table 1). By comparison October air temperatures were much cooler, 8° C lower on average than September. Although precipitation is only slightly higher, the average 5 cm soil temperature in October was 7° C lower.

By November the average air temperature is around 3.4° C, which begins initiating dormancy in winter peas. Extreme low temperatures of -13.8° C occurred in 2024, and -18.8° C in 2025. Green-up and adventitious shoots from ground level typically began in mid-March.

Table 1. FRT-03 Weather Station (2020-2024) Average Air Temperature (°C), Precipitation (mm) and 5 cm Soil Temperature (C°) https://coagmet.colostate.edu/cgi-bin/monthly_coag.pl.

	Avg. Air Temp. (°C)	***Avg Precip. (mm)***	***Avg 5 cm Soil Temp. (°C)***
September	18.2	22.1	23.7
October	10.2	26.2	16.3

when the average air temperature reached 4.9° C. Winter peas have an extended cool-season life cycle, combined with cold hardiness, allowing them to capitalize on seasonal patterns of higher precipitation and lower air temperatures in both fall and spring. Consistently cool air temperatures are necessary for satisfactory vegetative growth in field peas and winter peas are poised to take advantage of the season.

Table 2. Fruita (FRT-03) Weather Station (2020-2024) Average Air Temperature (°C), February-July.

	February	*March*	*April*	*May*	*June*	*July*
Temp.	0.0	4.9	9.5	14.9	21.3	24.8

Hnatowich (2000) reported the ideal average air temperature range for vegetative growth of field peas is 13-23°C, while temperatures greater than 27°C result in reduced flowering and shortened flowering periods. The top dry pea producing area in Montana in 2023 was Sheridan County, with 75,085,866 kg (USDA, 2023). Weather records from Sheridan's County seat of Plentywood (48.7736° N, 104.5602° W, 928 m elev.) indicate growing conditions that support cool-warm, moist growing conditions contribute to produce higher yielding dry peas.

Table 3. Monthly Mean Air Temperature (°C) Mean Precipitation (mm), 1991-2020, Plentywood, MT

	February	**March**	**April**	**May**	**June**	**July**
Temp.	-9.8	-2.9	4.7	11.1	16.3	19.6
Precip.	8.9	15.2	25.9	51.8	78.0	64.5

By planting during an appropriate window in the fall or spring, growers can reduce dependence on irrigation resources as winter peas finish vegetative growth earlier in the summer. Winter pea variety 'Kurtwood' can be planted in fall (mid-September) or early spring (mid-

March), when soil temperatures reach 7.2° C and increased natural precipitation trends favor plant growth with less supplemental irrigation. Culturally, changing the time of planting of dry peas to fall versus spring planting, may allow for a cascade of desirable outcomes for legume crop management: earlier harvesting the following summer, reducing the total irrigation volume, and allowing for maturity and senescence at times when air temperatures are seasonally more moderate. Planting winter peas in the fall may give growers some possible advantages over spring planting including overall yield increase, earliest possible spring emergence and growth, heat avoidance, and cool soil avoidance that limits stand density and emergence in spring plantings (Chen et al., 2012).

Benefits of Planting into Cereal Stubble

Planting legumes into cereal stubble also regulates plant water usage, giving growers a chance to reduce evaporation, which may allow for expansion of field peas and lentils into greater semi-arid, dryland settings (Cutforth et al., 2002). Reduced wind speed, solar radiation, and reduced potential evaporation of cereal stubble are additional key environmental benefits for legume crops sown in their understory (Cutforth and McConkey, 1997; Cutforth et al., 2002). Taller residue treatments may also be responsible for greater water use efficiency (WUE) or grain yield per unit of crop water. Field peas used the same amount of water in varying residue height treatments (15-18 cm versus 25-36 cm) though the crops sown into the taller cereal residue increased yield and thus water use efficiency 16% over conventional tilled plots (Cutforth et al., 2002).

Soil temperatures have also been shown to decrease from seeding to harvest as residue height increases versus cultivated stubble, creating more optimal soil moisture conditions for pea growth (Cutforth et al., 2002). Stubble also increases the storage of snow for fall-sown legume crops, creating a natural snow fence. As cereal residue height increases, the amount of wind-blown snow trapped in its matrix also increases (Steppuhn, 1994). This stored winter precipitation may directly support N fixation needs in legumes, while also leaving valuable soil water behind for cereal crops that follow (Biederbeck et al., 2005).

The research project examined three research questions involving winter peas: i. Do winter peas planted no-till in standing cereal residue yield more than winter peas planted in conventionally tilled cereal residue, ii. Do winter peas have significant differences in water use efficiency when planted in standing wheat and triticale residue versus winter peas planted in conventionally tilled cereal residue, iii. Is it economically profitable to incorporate winter peas as part of a cereal-winter pea rotation in place of a continuous winter wheat rotation?

MATERIALS & METHODS

Agronomy

All experimental plots were located at the Colorado State University Western Colorado Research Center, Grand Valley (WCRC-GV), Fruita, CO. Soils were Sagers silty clay loam and classified as prime irrigated farmland by NRCS soil survey (2025). In the 2024 growing season plots had triticale residue and in 2025, winter wheat. Plots were harvested for grain and straw in July. Afterwards field plots were randomly divided into blocks of either straw residue tilled into the soil with three passes of a tandem disc harrow or no-till planting winter peas into cereal straw left as tall as possible from grain and straw baling harvesting operations. Cereal residue height approximated 35.5 cm. The straw height of 35.5 cm was chosen based on the average height of the combine header sufficient to harvest either triticale or wheat grain, while leaving the maximum allowable cereal stem (residue) height possible to plant winter peas into. Straw was baled in the first year of the study with a tall crop of triticale stems necessitating the operation, but straw was not baled the second year due to lower straw height and difficulties in accessing the plots with large straw baling equipment.

In year one, three experimental and three control plots were planted on 9/30/23. In year two, three experimental and five control plots were also planted on 9/30/24. Plot size was 30.5 m long by 9.1 m wide or .03 hectare (ha). Rectangular shaped plots were planted and harvested crosswise in long strips of either residue or disced blocks. Randomizing tillage treatments across the field as in a randomized complete block design (RCBD) did not appear feasible due to the inability to mitigate or adjust for carryover or spillage of soil and residue from tillage operations.

All plots in the study were planted with Kurtwood winter pea seed (Progene, Othello, WA 99344), which were pre-inoculated by hand just before planting with Exceed granulated pea inoculant (Visjon Biologics, Henrietta, TX 76365) consisting of *Rhizobium leguminosarum biovar viceae* $2 \times 10^{\wedge 8}$ CFU/g. Seed was inoculated at the manufacturer's recommendation at a rate of 77 g of inoculant per 22.7 kg of seed, with 28 g of distilled water to facilitate adhesion of the inoculant to the seed.

Planting for all plots in both years was with an Esch 5607 (Bethel, PA 19507) no-till drill, with seeding setting at 68 kg ha^{-1} with 12.7 cm row spacing. Planting depth was the second shallowest setting on the machine approximating about 2.5 cm. The 5 cm soil temperature at the FRT-03 weather station, at planting time, was 16.1° C in 2023 and 25° C in 2024. In 2023, peas emerged from the soil by 10/6. In 2024, peas emerged by 10/10.

Residue cover transects were conducted for both years of the study to quantify the amount of residue in both experimental (no-tillage) and control (tillage) plots. Both transects occurred after planting in the fall (11/1/2023), and early winter (2/28/2025). Percent residue cover analysis was based on the method of Shelton & Jasa (2009).

Soil sampling for soil texture and soil fertility was conducted in late winter to the 0-20 cm depth. Soil texture was examined in each study year with the hydrometer method as described by Gee and Bauder (1986). Three soil cores were taken randomly from each plot, mixed and sent to Ward Laboratories (Kearney, NE, 68847) for macronutrient analysis. Soil testing results for 2024 (Table 4) and 2025 (Table 5) reflect the soil conditions for the plots in late winter before any adjustment for N, P (phosphorous), or K (potassium) fertility.

Table 4. Soil sample analysis from Disc and Residue (“Res”) plots, February 2024.

Plot	***Soil pH***	***OM, %***	***Nitrate, mg kg^{-1}***	***Olsen P, mg kg^{-1}***	***Potassium, mg kg^{-1}***	***Sodium, mg kg^{-1}***
17 Res	6.9	1.8	41	11.3	150	156
18 Res	7.7	1.9	38	9.6	161	190
19 Res	7.8	1.7	43	11.2	171	187
45 Res	7.9	2	20	7.7	193	97
48 Res	8	1.7	20	8.3	139	107
20 Disc	7.8	1.9	35	14.8	180	143
21 Disc	7.8	2.3	69	16.9	230	203
22 Disc	na	na	na	na	na	na

Table 5. Soil sample analysis from Disc and Residue (“Res”) plots, February 2025.

Plot	***Soil pH***	***OM %***	***Nitrate, mg kg^{-1}***	***Olsen P, mg kg^{-1}***	***Potassium, mg kg^{-1}***	***Sodium, mg kg^{-1}***
11 Res	7.7	2.1	148	14.6	134	173
12 Res	8	1.8	38	12.7	133	150
33 Res	na	na	na	na	na	na
14 Disc	8	1.9	45	11.3	152	116
15 Disc	7.8	1.9	53	8.8	142	146
53 Disc	7.8	1.4	86	8.3	73	219
61 Disc	7.8	1.7	53	9.5	132	136
63 Disc	7.6	1.7	82	10.1	163	153

Fertilizer was applied according to soil test recommendations established by the Pulse Crop Production Field Guide (A1922) for North Dakota State University (2019). No plot had less than 17 kg ha^{-1} N to the 60.9 cm depth, so winter peas only received indirect N from phosphate application of monoammonium phosphate (MAP, 11-52-0) to adjust soil P. Plots with Olsen soil P concentration between 8-11 mg kg^{-1} received 22.68 kg ha^{-1} P_2O_5 while plots with 12-15 mg kg^{-1} received a lower 11.34 kg ha^{-1} P_2O_5 rate, and plots $\geq$ 16 mg kg^{-1} received no additional P fertilizer. No plots were recorded as having < 8 mg kg^{-1} Olsen P. Potassium was only added to soil with less than < 100 mg kg^{-1}, which occurred once per year of the study, necessitating application of a 30 kg ha^{-1} K_2O rate in the form of KCl (0-0-60).

Herbicide Program

Control of weeds required an herbicide program that was created that included pre-emergent, grass, and broadleaf weed control specifically for dry peas. After planting, all plots were sprayed with Pendimethalin (BASF, Geismar, LA, 70734) at 3,360 g ha^{-1} for pre-emergent grass and broadleaf weed control and watered in. Volunteer wheat and triticale were controlled prior to crop emergence with Clethodim (Loveland Products, Greeley, CO 80632) at a rate of 224 g ha^{-1} with 896 g ha^{-1} of both urea ammonium nitrate (UAN) and crop oil concentrate (Van Diest, Webster City, IA 50595) for adjuvants. At the end of May, before flowering began, 1,344 g ha^{-1} Bentazon (BASF, Geismar, LA, 70734) and 280 g ha^{-1} Imazamox (BASF, Geismar, LA, 70734) at were applied in a tank mixture as a post-emergent control with non-ionic surfactant at 1,120 g ha^{-1} and 5,600 g ha^{-1} of UAN before canopy closure to control broadleaf weeds preceding harvest.

Flowering began in early June in both study years. By the end of July 2024, when pods were 80% tan in color and leaves 30% green, Carfentrazone (FMC, Philadelphia, PA, 19104) was applied at 210 g ha^{-1} as a harvest aid to desiccate pea plants for the 2024 season. In 2025, drier and warmer weather made a harvest aid unnecessary as peas dried rapidly.

Replanting and Harvesting

In study year one, fall planting one depth setting too deeply with the no-till drill in all plots, emergence was spotty, and stand density was visibly diminished below a reasonable level for economic return. No measurements of stand reduction were taken. All plots were replanted on 03/12/2024 with the same Kurtwood variety winter peas at the same seeding rate and Esch 5607 no-till drill, but this time into a soil temperature of only 7.7° C. Peas began to emerge around 03/29/2024. In the 2025 growing season, three experimental plots with residue also had to be replanted, likely because of excessively dry, cold weather. Unexpectedly, the control plots had good survivorship from fall 2024 into spring 2025 and, therefore, did not need to be replanted from their original 9/30/2024 planting date.

Winter peas were direct harvested with the Wintersteiger (Salt Lake City, UT 84116) Classic Combine on 07/26/24 and 07/28/25. Harvest weights were measured with a Harvest Master (Logan, UT 84321) HM 800 Classic Grain Gauge. Plots were harvested into as many 9.1 m long by 1.5 m wide passes of the plot combine as possible.

Soil Water Properties

Soil available water content (AWC) was calculated by Midwest Laboratories (Omaha, NE 68144) with pressure plate extraction method to estimate field capacity (FC) and permanent wilting point (PWP). To determine bulk density of soil, the Mass per unit Volume Determination was used following the procedure described by Gupta (2000). Air-dried soil was sieved to <2 mm, and a known mass of the oven-dried sample (105 °C for 24 h) was placed into a standardized container of known volume. Bulk density was calculated as the ratio of oven-dry mass to total sample volume (ρb = Md/Vt). This method provides a consistent and practical estimate of soil compaction and porosity with disturbed soil samples. Bulk density, in g cm^3 based on the average of ten soil samples, was determined to be 1.28 (0-15 cm), 1.31 (15-30 cm), 1.31(30-45 cm) and 1.26 (45-60 cm). As bulk density of soil increases, soil pores are compressed and limit the amount of water the soil can store as well as limiting water infiltration and percolation through soil horizons.

Volumetric Water Content Measurement

VWC soil moisture readings were taken in plots at 15 cm from April to August, nine times in 2024, and three times in 2025 with an Acclima True TDR Soil Moisture Sensor Reader. The Acclima was used to avoid false readings that occur at shallow depths (i.e., 15 cm or less) using the hydroprobe. VWC readings are summarized in Figure 4 in the Results section.

VWC was converted to mm soil water per 6 cm of soil (mm cm^{-1}) using the formula:

$$\text{Total Soil Water (0-91cm)} = \sum_{i=1}^{6} \frac{VWC}{100}\ x\ 6\text{cm}$$

For example, a VWC of 18.58% measured in 0-15 cm soil depth = 0.1858(6) = 1.148 (25.4) = 28 mm cm^{-1} soil.

Welch's two-tailed, two-sample t-test, and linear regression with treatment as predictor variable of VWC at 15 cm, are reported in the Results section of the paper.

VWC soil moisture readings for 30 cm and deeper were taken five times during each growing season, April-August. Soil moisture readings began on 4/17/24 and 4/9/25, respectively. Irrigation also began on the initial sampling dates. Fields were irrigated to bring the soil to field capacity in the top 30 cm of soil, the estimated rooting depth for dry peas at this stage of development. Millimeters available soil water per 30 cm depth were assumed according to applicable Colorado Available Water Content (AWC) tables (Chavez et al., 2015), where: low AWC (3.25 mm), average AWC (4.06 mm), high AWC (4.57 mm), respectively.

A 503 Elite Hydroprobe (InstroTek, Denver, CO 80229) soil moisture neutron probe was utilized to take soil water readings before planting and after harvest at five soil depths within each winter pea plot: 30, 45, 60, 76, 91 cm, respectively. Each VWC reading was taken at the midpoint of each 15 cm soil interval. These readings were averaged to create a single VWC value for each depth and date. In year one of the study, one drill hole per plot was drilled to at least a depth of 91 cm with a handheld auger operated by two individuals and then encased in 3.8 cm diameter schedule 40 PVC tubing. In year two, all three residue plots, and two of the five disced plots, had three neutron probe tubes installed in each. Probe tube holes were drilled away from plot edges but otherwise were randomly assigned wherever pea plants had covered the soil (Appendix A). In year two having more than one probe tube in each plot was done to introduce replicates in plots to examine water use efficiency effects on a subplot basis. Tubing was capped and soil tamped around the PVC tubing to prevent precipitation or irrigation from directly entering the PVC probe tube.

Plots were managed with 40-50% management allowable depletion (MAD) in mind, and down to 60% as the peas began to dry down finish. To achieve this goal, data from the hydroprobe was used to estimate soil water with the help of the moisture linear equation below. Coefficients for variables A and B were provided by the manufacturer.

$$M= (A*\text{Hydroprobe reading (Reading/Std Count)} + B$$

Where M = Moisture (mm/30 cm)

A = (Slope)= 3.3611

B = (Intercept)= - 0.094

A,B values are for SCH 40 PVC.

Calibration of count rate against VWC soil and cumulative error estimates approximated, plus or minus, 3.81mm each week over 130 cm of soil depth. Calibration and conversion methods supported further analysis of rooting-zone water depletion by winter peas in the Discussion portion of the paper.

Water and water use efficiency

To accurately account for water use in plots, soil infiltration rate and wind speed during irrigation were examined.. Soil infiltration rate for silty clay loam soil was assumed to be 6.35 mm hr^{-1}. For example, the first 2025 season watering of 133 mm in April 2025 to fill the soil profile from fall and winter drought, was calculated to have shed 57 mm or 43% of the irrigation volume due to slower soil water infiltration and the high sprinkler delivery rate of 11.2 mm hr^{-1}.

Two metrics of crop water usage were formulated from the water balance data. One was to calculate water use efficiency second was to calculate crop water use efficiency (CWUE). The water balance equation models evapotranspiration (ET) in winter peas for both years of the study:

$$ET = \Delta S + \sum P_e + \sum I_e$$

Where ΔS = change in VWC (volumetric water content) water storage * 15-cm depth increment)

$\sum P_e$= sum of Precipitation X 0.85 error factor (i.e., 15 % for evaporation, wind losses)

$\sum I_e$= sum of Irrigation X 0.85 error factor (i.e., 15% for evaporation, wind losses)

The water balance was calculated on a plot-by-plot basis for the study using neutron probe data. First, VWC is measured in selected plots with the hydroprobe before planting at five soil depths and then again at these depths after harvest. The VWC ending value is subtracted from the beginning value for each depth and then multiplied by 15 cm increment between them and then summed to give the value ΔS (Delta S). Second, $\sum P_e$ (Sigma Precipitation, sub e), was calculated as the sum of precipitation from planting to harvest at the FRT-03 weather station multiplied by 0.85 for a 0.15 error factor for evaporation and wind losses (Coagmet, 2025). The sum of $\Delta S + \sum P_e$, adjusted precipitation was then added to the adjusted irrigation sum, $\sum I_e$, the value of irrigation applied from planting to harvest was multiplied by 0.85 for a conservative 0.15 error factor for evaporation and wind losses. Precipitation millimeters for the growing season from the FRT-03 weather station were converted to mm by multiplying by 25.4. Winter pea yield (kg ha^{-1}) was divided by mm ET to find kg ha^{-1} mm^{-1} to determine water use efficiency (WUE) for each plot:

$$\text{WUE} = \frac{\text{pea grain yield (kg ha}^{-1)}}{\text{ET (mm)}}$$

$$\text{WUE} = \text{kg ha}^{-1}\ \text{mm}^{-1}$$

Water Use Efficiency (kg ha^{-1} mm^{-1}) was evaluated with two-sample, two-way Welch's t-test between residue and disced plots for individual years 2024, 2025 and both years combined. Cohen's d was used to interpret the magnitude of t-test results.

Enterprise budget analysis

An enterprise budget was created for growing winter peas to determine expenses on profits of a single crop, winter peas. The enterprise budget is also useful in determining the break-yield amount of edible winter pea grain. Upon calculating the break-even point for winter pea production, it was determined that additional information would be necessary to more accurately model the net change in profit by creating an agricultural partial budget (Kay et al., 2019).

Partial budget analysis

The addition of the partial budget provided a more accurate answer to the question of the expected economic outcome if a producer were to switch to a winter wheat (WW) - winter pea (WP) rotation versus a more traditional continuous wheat system. The partial budget compared the alternative crop rotation of winter pea-winter wheat by measuring additional costs and reduced revenue sum (Value A) and subtracting it from the additional revenue sources and reduced costs (Value B) to determine any net change in profit, positive or negative (Kay et al., 2019).

Agriculture Budgeting

The set of equipment and machinery used in the enterprise budget for winter peas included: John Deere 2955 tractor, King Kutter tandem disc harrow, Honda foreman ATV (all-terrain vehicle) with Workhorse boom sprayer. The tractor chosen for the study was a John Deere (JD) 2955 tractor, produced in 1987-1992, and was used principally as the tractor for all planting and tillage during the cereal winter pea rotation in the study. The JD 2955 was chosen for its 86-horsepower take-off (PTO) horsepower, type II hitch and 259 cm wheelbase size, to work within the smaller 0.03 ha size plots. Purchase price of the JD 2955 was $39,000 new, while salvage value was determined by multiplying the purchase price of the tractor times 0.34 for a tractor >12 years to be $13,260. Depreciation per hour (DPH) was also calculated for use in the partial budget to determine net change in profit due to less or more tractor operations in the field. DPH was calculated by subtracting salvage value from purchase price divided by the potential total operating life span in hours (e.g., 10,000 hours). Taking the purchase price of $39,000-$13,260=$25,740/10,000 lifetime operating hours=$2.57 DPH. To determine tractor fuel usage, the average gallons per hour (GPH) were calculated as 0.044 X PTO hp (diesel)= 0.044 X 86 hp = 3.8 GPH.

Implements used in the study included a 2023 152 cm width King Cutter (Winfield, AL, 35594) tandem disc harrow with 45 cm notched coulters in the front and 40 cm round discs in the rear, which was used for tillage treatments and retails for $2299.99 new and is assumed owned and approximately two years old for the study. Depreciation, capital recovery factor (CRF), taxes, insurance and housing for the tandem disc harrow and other tractors and machinery was calculated as defined in Iowa State University Extension PM 710 (2015). The implement's age (2 years) was known but not the usage amount per year.

Expected usage of the tandem disc harrow over 2 years was multiplied by expected annual use (e.g., 25 hours), in this case equaling 50 hours. CRF is the amount of dollars needed to repay value on the implement which is lost due to depreciation, to pay interest costs or opportunity costs on the purchase of the implement. CRF in this case is based on 13 years and a real interest rate of 4.25% which was calculated by subtracting the expected current rate of inflation, 3%, from the average interest rate of 7.25%, providing a CRF coefficient of 0.100. Capital recovery costs were then calculated as: CRF X purchase price – salvage value after 13 years: (0.100 X (2,299.99-713)) + 713 X .0425) = $158.70 + $30.30 = $189 CRF.

Taxes, insurance, and housing (TIH) for the implement were calculated as TIH = one percent X (purchase price + salvage value)/2 = 0.01 X (2299.99 + 713)/2=$15.06. The one percent coefficient in the equation primarily accounts for insurance on farm machinery as tractors, farm machinery and implements are exempt from property tax in the state of Colorado. Total fixed costs for the tandem disc harrow are equal to the sum of CRF and TIH. $189 + $15.06 = $204.06. Variable costs, which included fuel, lubrication, labor, and repairs came to $28.98.

A 2002 Wintersteiger Classic Combine was used to harvest winter wheat and is owned for the purposes of this study, originally purchased for $50,000. Expected usage of the combine over 2 years was multiplied by expected annual use (e.g., 25 hours), in this case equaling 50 hours. The CRF table provided a CRF coefficient of 0.074. Capital recovery costs are then calculated as: CRF X purchase price – salvage value after 20 years. (0.074 X (50,000-5,000)) + 5,000 X .0425) = $3,330 + $212.5 = $3,542.50 Capital Recovery per year.

TIH for the combine was calculated as TIH = one percent X (purchase price + salvage value)/2=0.01 X (50,000 + 5,000)/2=$275. The one percent coefficient in the equation primarily accounts for insurance on farm machinery such as combines, which are exempt from property tax in the state of Colorado. Total fixed costs for the Wintersteiger Classic Combine are equal to the sum of CRF and TIH. $3,542.50 + $275 = $3,817.50. Variable costs, which included fuel, lubrication, labor, and repairs came to $191.98.

A 2022 Honda Foreman ATV (Honda, N.C., 27359) and rear-mounted Workhorse Sprayer (North Sioux City, SD, 57049) 100 quart, 7-nozzle boom sprayer were used for all herbicide applications. For simplification, as the machine and equipment are solely used together, they will both be discussed and their values added together, respectively. For the purposes of this study, the Honda Foreman all-terrain vehicle (ATV) is owned and originally purchased for $7,300, and the 2022 Workhorse Sprayer is owned and originally purchased for $499 for a grand total of $7,799. CRF was calculated as the amount of dollars needed to repay value on the ATV and sprayer which are lost due to depreciation, to pay interest costs or opportunity costs, on the purchase of both pieces of equipment. CRF in this case is based on 13 years and a real interest rate of 4.25% which was calculated by subtracting the expected current rate of inflation, 3%, from the average interest rate of 7.25%, providing a CRF coefficient of 0.100. Capital recovery costs are then calculated as: CRF X purchase price – salvage value after 13 years: (0.100 X (7,799-1,871.76)) + 1,871.76 X .0425) = $59.27 + $79.55 = $138.82 CRF.

TIH for the ATV were calculated as TIH = one percent X (purchase price + salvage value /2: 0.01 X (7,799 + 1,871.76)/2=$48.35. The one percent coefficient in the equation primarily accounts for insurance on farm machinery as tractors, farm machinery and implements are exempt from property tax in the state of Colorado. Total fixed costs for the ATV and sprayer are equal to the sum of CRF and TIH: $138.82 + $48.35 = $187.17. Variable costs for both pieces of equipment, which included fuel, lubrication, labor, and repairs came to $63.

The only custom hired equipment for the study was the Esch (Bethel, PA, 19507) 5607 no-till drill, used for planting all plots. The planter was rented locally for $50 per day, plus $12.50 per hectare, assuming one hectare planting area equals $62.50.

RESULTS

2024 Results

The mean yield of winter peas harvested in 2024 was 910.9 kg ha^{-1} in residue plots and 483.2 kg ha^{-1} winter pea grain harvested from the disced plots (Table 6). Welch's two-tailed, two-sample t-test showed a significant difference in winter pea grain yield in 2024 between the residue group and disced group (t (126) = -7.05, p < .001). Yield values were examined for outliers and extreme values. One outlier was noted in a residue plot, the remaining six all in disced plots, while no extreme outliers were noted in any of the plots. Percent cover from line transects averaged 70.4% for residue and 49.0% for disced plots, respectively.

Table 6. Mean winter pea grain yield kg ha^{-1} by tillage treatment.

	treatment	*n*	*mean yield*	*S.D.*
2024	Residue	90	910.9 kg ha^{-1}	364.9
	Disc	60	483.2 kg ha^{-1}	363.7
2025	Residue	41	452.3 kg ha^{-1}	162.9
	Disc	68	666.1 kg ha^{-1}	401.6

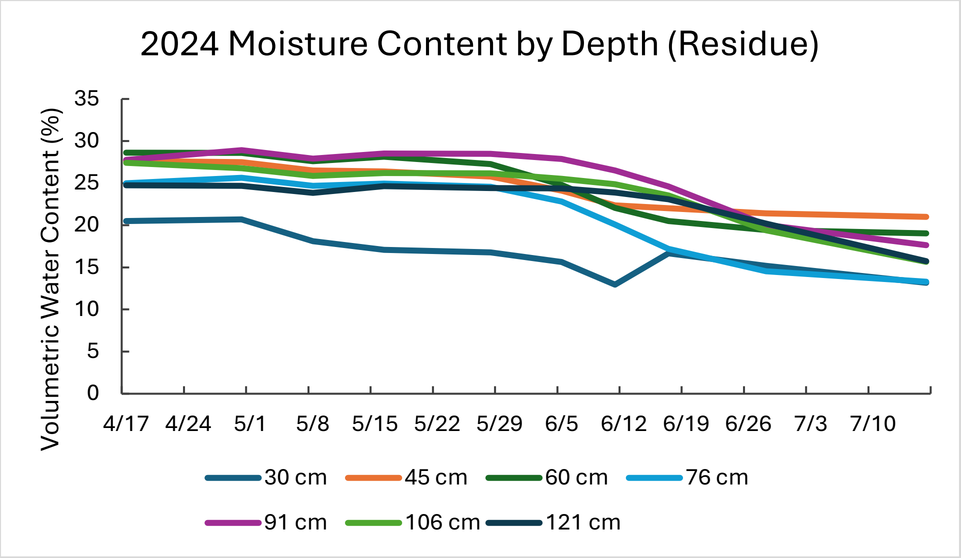
Quantile-quantile (QQ) plot of residue and disced plots show no major funnels or curves away from the reference line (Figure 1), indicating yield data followed a normal yield distribution. To assess variance, an F test, F(59, 89)=0.99, p=0.99, was conducted and confirmed variances of the disced and residue groups were homogeneous in 2024. Levene's test

F(1,142)=0.30, p=0.58 also supported the assertion of no significant difference in variation between groups.

Water use efficiency averaged 1.82 kg ha^{-1} mm^{-1} in 2024 in residue plots and 1.13 kg ha^{-1} mm^{-1} in disc plots, with a two-tail, two-sample Welch's t-test t($p=0.07$). T-test of three disc versus five residue groups found no significant difference ($t(6)=-1.72$, $p < 0.14$) in water use efficiency.

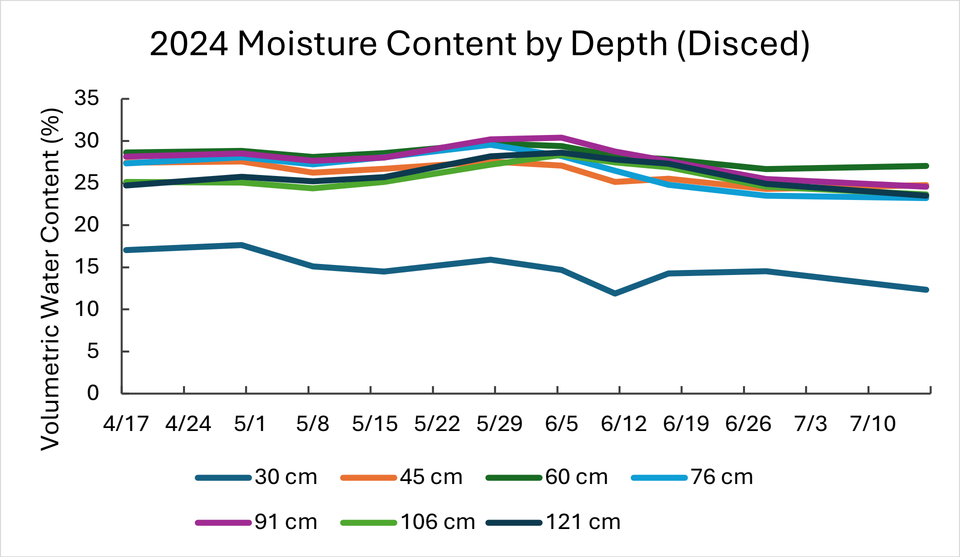
Welch's two-tailed, two-sample t-test showed a statistically significant difference in soil VWC at 15 cm depth between the residue group and disced group, $t(82)= 3.18$, $p = 0.002$. Soil VWC at 15 cm in the disced group were on average -0.048 lower than the residue group. Average volumetric water content in mm during April-May 2024, is depicted below for residue plots (Figure 1) and disced plots (Figure 2). Based on 2024 yields, gross revenue was \$141.55 ha^{-1} on average for grain from disc plots and \$266 ha^{-1} for grain from residue plots.

Figure 1. 2024 Moisture Content by Depth (Residue).



Estimated enterprise budget profit ha^{-1} for 2024 was $-624.34 and $-501.98 for disc and residue yields, respectively.

Figure 2. 2024 Moisture Content by Depth (Disc).



2025 Results

Winter pea grain weights were on average 213.8 kg ha^{-1} higher in disced plots than residue plots (Table 5). Disced plots averaged 666.1 kg ha^{-1} and residue plots 452.3 kg ha^{-1}, respectively. Welch's two-tailed, two-sample t-test showed a significant difference in winter pea grain yield in 2025 between the disc group and residue group (t(107)=3.25, p=.002). No outliers or extreme outliers were noted in plot yields for 2025. Percent cover from line transects averaged 70.5% for residue and 24.9% for disced plots. Normality distribution for grain yield was visually assessed with a QQ plot (Figure 5) that showed normal distribution. Levene's test also supported a significant difference in variances F(1,107)=22.95, p=<.001.

Welch's two-tail, two-sample t-test comparing water use efficiency (kg ha^{-1} mm^{-1}) of five disc and three residue plots showed no significant difference t(6)=0.3, p=0.78.

Although soil VWC at 15 cm in the residue group was on average 0.03 higher than the disc group, Welch's two-tailed, two-sample t-test did not indicate a statistically significant difference in VWC at 15 cm in 2025 between the residue group and disced group, t (4) = -1.65, p = 0.10. Average volumetric water content in mm during April-August is depicted below for residue plots (Figure 3) and disced plots (Figure 4).

Figure 3. 2025 Moisture Content by Depth (Residue).

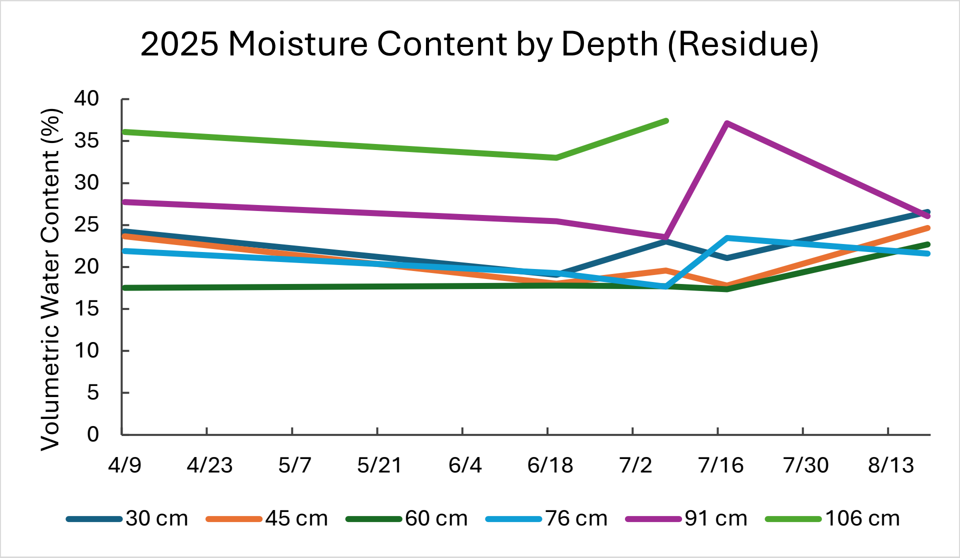
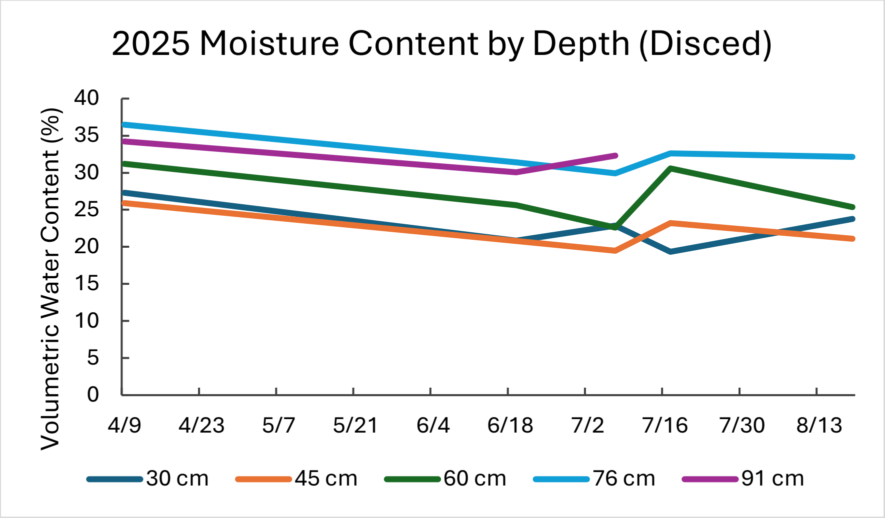


Figure 4. 2025 Moisture Content by Depth (Disc).

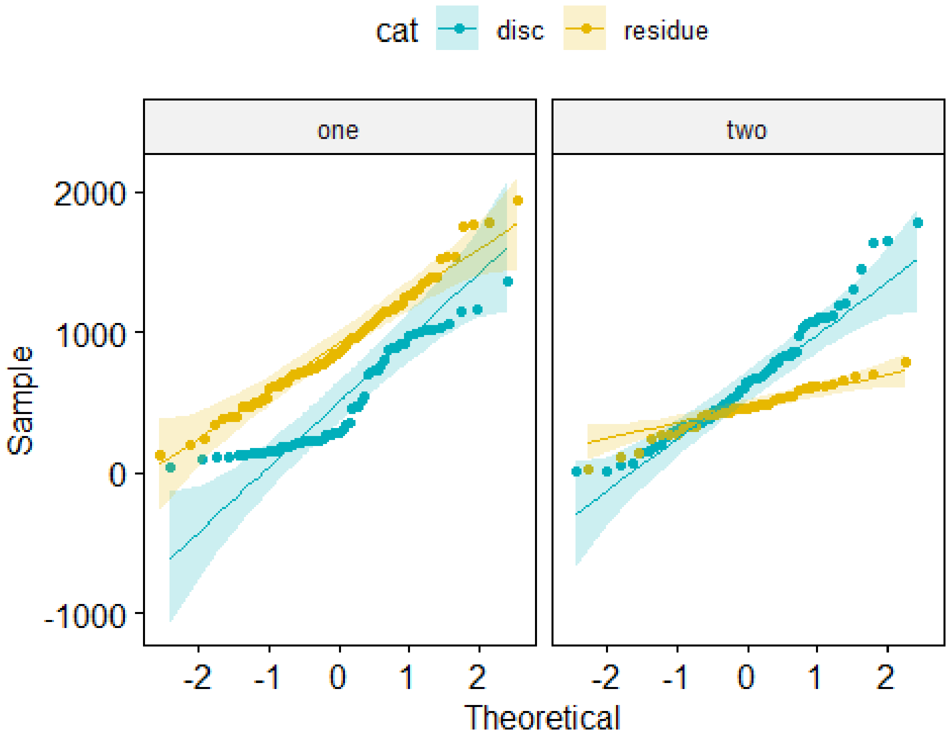


Gross revenue was calculated on the September 2025 average farm-gate market value of \$194.18 for disced plots and \$133.0 for residue plots, respectively. Estimated profit was \$-573.80 ha^{-1} and \$-634.98 ha^{-1} for disced and residue plots, respectively.

2024-2025 Combined Results

Residue plots, on average, yielded 187 kg ha^{-1} more than disced plots (Table 7). When combining both years of yield data into one F test (F(127,130)=1.07, p=0.70), there was no significant difference in variance between groups. Levene's test for homogeneity of variance for both years also showed no significant difference F(1,257)=1.03, p=0.31. A two-tail, two-sample Welch's t-test t(256)=-3.89, p < .001) showed a significant difference in winter pea grain yield between groups overall.

Figure 5. QQ Plot of yield, Disc and Residue treatments, year "one" = 2024, "two"=2025.



Percent cover from line transects averaged 70.5% over both years and 37.0% for disced plots, though disced plots in 2025 averaged 24.9%. Soil texture from the hydrometer method in nine of the fourteen plots indicated either Sandy Clay or Sandy Clay Loam soil texture with the remaining plots being Clay or Clay-Clay Loam texture.

WUE was 1.82 kg ha^{-1} mm^{-1} for residue plots and 1.13 kg ha^{-1} mm^{-1} for disc plots in 2024 but showed no significant difference (p=0.07). Results for 2025 are shown in Table 8.

Precipitation efficiency (Peff) and irrigation efficiency (Ieff) for both treatments were similar (Table 9). Ieff was slightly higher in 2025 for residue plots under the linear sprinkler. Peff values were consistent over the two years of the study. Runoff (RO) was determined to be minimal during the growing season as well as minimal deep percolation (DP) within soil horizons.

Table 7. 2024-2025 Average Yield, kg ha^{-1}

Treatment	*N*	*Avg Yield*	*Standard Deviation*
Disc	128	580 kg ha^{-1}	393.7
Residue	131	767 kg ha^{-1}	380.7
Overall	259	675 kg ha^{1}	397.6

Evapotranspiration (ET) was similar between residue and disced plots in 2024 averaging 262 mm but averaged 429 mm in 2025. Delta soil water (ΔSW) values indicate that except for the 2025 disced treatment, all other disced and residue plots had negative values indicating soil moisture had been lost during the growing season.

Table 8. 2024-2025, Two-way T-test and P-value, WUE kg ha^{-1} mm^{-1}

Category	*2024 Avg WUE kg ha^{-1} mm^{-1}*	*2024 T-Stat, P-value*	*2025 Avg WUE kg ha^{-1} mm^{-1}*	*2025 T-Stat, P-value*
Disc	1.13	-2.2	0.82	0.63
Residue	1.82	0.07	0.63	0.55

Table 9. 2024-2025 Irrigation, Water Balance and Yield.

Year	*Category*	*Peff (mm)*	*Ieff (mm)*	*RO (mm)*	*ET (mm)*	*ΔSW (mm)*	*Yield (kg ha^{-1})*
2024	Residue	55	156	0	264	-54	910
2024	Disced	55	185	0	259	-20	483
2025	Residue	48	373	0	418	3.3	452
2025	Disced	48	371	4.51	445	-26	666

Peff"= Precipitation Effectiveness, "Ieff"=Irrigation Effectiveness, "RO"=Run off, "ET"=Evapotranspiration, "ΔSW"=Delta Soil Water, "Yield"=Winter Pea Grain Yield,

Enterprise Budget

Variable and fixed costs were calculated to better understand the cost and profits of winter pea production for edible grain (Table 10). Other similar enterprise budgets were formulated for each treatment, in each year but are not shown. Net returns are summarized in Table 11. Variable costs were split into two categories: seed, fertilizer, pesticides (subtotal A), and fuel, lube, repairs, irrigation and labor (subtotal B). Subtotal A, which included winter pea seed, fertilizer (monoammonium phosphate [MAP] 11-52-0), herbicides, desiccant costs came to \$255.76 ha^{-1}. Subtotal B, the sum of diesel fuel, oil, grease, repairs, irrigation, labor, and harvest costs came to \$255.97 ha^{-1}. Added together total variable costs came to \$511.73 ha^{-1}. Fixed costs (subtotal C) included machinery depreciation, interest, taxes, and insurance, came to \$256.25 ha^{-1}, were added to variable costs (subtotals A & B) for a total cost of \$767.98.

Table 10. 2024 Enterprise Budget: Residue Treatment

Variable Costs (A): Seed, fertilizer, herbicides.	\$255.76	***Total Cost ha^{-1} (A + B + C)***	\$767.98
Variable Costs (B): Fuel, oil, repairs, irrigation, labor.	\$255.97	***Total Yield Revenue ha^{-1} (D)***	\$266.00
Fixed Costs (C): Machinery depreciation, land interest, taxes, insurance.	\$256.25	***Estimated Profit ha^{-1} (D – A + B + C)***	\$-501.98

Table 11. Edible Winter Pea Net Return (dollars ha^{-1})

	2024	2025
Residue	\$266.00	\$132.21
Disc	\$141.55	\$194.18

Partial Budget

A partial budget was used to calculate costs and revenue of the alternative crop cycle WW-WP by measuring additional costs and reduced revenue (i.e., Value A) and subtracting the sum value from the additional revenue sources and reduced costs (i.e., Value B) to determine any net change in profit, positive or negative.

Additional costs identified in the wheat-winter pea rotation included renting a no-till drill for \$62.50 ha^{-1} (Lifetime Ag, Loma, CO, 81524). Reduced revenue from continuous hard red winter wheat grain yield reduction of 15,000 kg ha^{-1} / 27.2kg = 551.47(\$4.37 per 27.2 kg) = \$2,409.93 loss of grain. Straw bales 1 m x 1 m x 2.4 m long straw bales at \$40 per bale (2025 market price, Fruita, CO) x 100 bales per hectare = \$4,000. The grand total for Value A therefore comes to \$6,409.93.

Additional revenue came from regional farm gate pricing on edible winter peas at \$14 per 45.4 kg weight (100 lb.)= \$280.40. After grain harvest, combined threshed residual forage dries quickly and provides a protein rich forage for livestock. Using a conservative 2,900 kg pea forage ha^{-1} divided by 9.8 kg forage (i.e., 2.16% of bodyweight for a 453.5 kg beef cow's daily dry matter intake) = 295 beef cattle feeding days ha^{-1} (McPhee and Muehlbauer, 1999). Dividing 295 beef cattle days by ten heifer cow herd size =29 days of potential feed. Further, multiplying 29 days of potential feed by \$2.91 (i.e., the average cost of feeding beef cow heifers per day in 2022 in Colorado), and again by a 10-heifer herd equates to \$843.90 value ha^{-1} (USDA, 2010). Additional revenue totaled \$1,124.30 ha^{-1}.

Reduced costs consisted of tillage with a tandem disc harrow being reduced 3-4 passes ha^{-1}, plus one pass of roller harrow ha^{-1} which equaled 4.5 hours ha^{-1} less tractor time. Diesel fuel GPH consumption for the JD 2955 used in the study was 3.8 gallons hr^{-1}, multiplied by 4.5 hours, at \$1.00 per gallon, equals fuel savings of \$17 ha^{-1}. Labor was valued at \$22.22 per hour times 4.5 hours equal to \$100 labor saved ha^{-1}. Nitrogen (N) credits of 40 kg ha^{-1} from dry peas can be anticipated and assuming 10.4 kg of N in each 22.7 kg bag of Urea (46-0-0) fertilizer, 3.8

bags Urea multiplied by $32.99 (local price, Oct 2025, Fruita CO) equals $125.36 ha^{-1} less N expense for winter wheat production (Bourion et al., 2007; Liu et al., 2019). Savings for tractor depreciation from tillage, fuel, labor, and fertilizer totaled $254.03 ha^{-1}. The grand total for additional revenue and reduced costs (Value B) was $1,378.33 kg ha^{-1} minus Value A, $6,409.93 =$-5,031.60 a negative net change in profit ha^{-1} by switching to a WW-WP rotation.

Breakeven Yields

Simple breakeven analysis and comparative analysis were calculated for yields. Results from both analyses are summarized in Table 12. For the comparative analysis, low average kilogram yield=3,000 kg ha^{-1}, medium 3,500 kg ha^{-1}, and high, 4,000 kg ha^{-1}, respectively, values were used. Farm gate prices (FGP) were based on the farm gate price per 45.4 kg of dry peas in Colorado during 2025 of $14.00 FGP + 10% ($15.40), FGP + 20% ($16.80), and FGP + 30% ($18.20), respectively. Comparative breakeven analysis examined the same FGP increases except for adding FGP + 40%, using 2,497 kg ha^{-1} yield.

Table 12. Economic Breakeven Analysis

	kg ha^{-1}	2025 CO Farm Gate Price (FGP): $14.00 per 45 kg, [# 45.4 kg weight]
Simple Breakeven	2,497	770-767.98=$2.02 [55]
Comparative Breakeven: Yield	3,000	925.11-767.98=$157.13 [66]
	3,500	1,079.30-767.98=$311.32 [77]
	4,000	1,233.48-767.98=$465.50 [88]

Comparative Breakeven: Price	2,497	FGP + 10%=847-767.98=$79.02 FGP + 20%=924-767.98=$156.02 FGP + 30%=1,001-767.98=$233.02 FGP + 40%=1,078-767.98=$310.02

DISCUSSION

While WUE tests showed no significant difference between winter peas planted in either disced or residue environments in any study year or combined years, there is reason to believe that residue environments may still hold promise for growing winter peas. Winter pea grain yields combined over two years were 325 kg ha^{-1} higher in residue environments on average than disced environments in both years. Higher yields in disced plots versus residue plots in 2025 may have been due to peas in disced plots having successfully overwintered whereas all three residue plots for comparison needed to be replanted in March 2025 due to low visual stand density. Replanting in Spring meant peas in residue did not have the head start of the disced plots planted in September. Although WW-WP rotations did not provide the significant economic savings hoped for on tillage, diesel, and fertilizer costs, the benefits of winter peas as a rotational tool should not be overlooked.

Limitations

The experimental design of the study faced several elements that could have been better anticipated for a more successful outcome. Ideally the study would've occupied a larger area with additional replications to increase statistical power by adjusting for different soil textures and their varying AWC, respectively. Having too few plots available to make compelling comparisons between residue and disced plots limited statistical power. Replanting plots in spring each year of the study highlights the importance of proper planting time. Earlier planting on September 15 (versus September 30 for each year of the study) may help winter peas to establish before freezing weather and could reduce stand losses over the winter. It may also be the case that winter peas have marginal cold hardiness. Temperatures at or below -15° C may greatly limit the overwintering capacity of winter peas.

Regional Implications

Planting winter peas as part of a cereal rotation over the two study years did provide practical evidence of their agronomic rotational value in several ways. Fall-planted winter peas following hard red winter wheat harvest gives farmers an opportunity to keep fields in production while easily controlling volunteer cereal regrowth and limiting wheat pathogens. Volunteer cereal plants that emerge and live between winter wheat harvest and replanting in fall, or along the edges of fields, are not subject to the same rigorous insecticide spraying as wheat fields under production. Wheat curl mites (*Aceria tosichellai)* prey on these volunteer wheat plants and are a vector of Wheat Streak Mosaic Virus (*Triticum mosaic virus* (TriMV) and High Plains Wheat Mosaic Virus (HPWMoV) which significantly reduce wheat yields (Castillo, 2023). Between wheat harvest in July and replanting in fall, Group one mode of action herbicides such as Intensity (Clethodim), Poast (Sethoxydim), Assure II (Quizalofop-p-ethyl), all selectively eliminate volunteer wheat while leaving broadleaf crops, like winter peas, unaffected. Intensity, Poast, and Assure II are all labeled for up to two applications per growing season in dry peas (Loveland, 2025; BASF, 2025; Dupont, 2025). Poast is also labeled for hand, spot-spraying applications for volunteer wheat in non-crop border areas where boom sprayers cannot reach (BASF, 2025). The use of group one herbicides and simple crop rotation to winter peas gives the farmer the opportunity to have fields mostly free of volunteer cereals and other monocot weeds, their subsequent pathogens, while supporting an N fixing legume crop that sharply breaks a continuous mono-cropping cycle.

Nitrogen is the most important macronutrient for plant growth and the addition of an average of 40 kg ha^{-1} nitrogen fixed by dry peas, although not large, constitutes enough N left behind in the soil to serve as a starter fertilizer for following crops (Bourion et al., 2007; Liu et al., 2019). Soil nitrogen left behind by peas such as ammonium and nitrate, are available to plant roots and requires no producer purchase or input of expensive synthetic fertilizers. Although synthetics fertilizers provide greater crop yields they also have numerous drawbacks including requiring additional spreading equipment, labor, fuel, soil compaction, and the environmental impact from their manufacturing and transportation to consumers.

Rooting Behavior and Soil Moisture Patterns

Comparing the two growing seasons of the study, 2024 could be characterized by lower irrigation, higher WUE, and perhaps deeper rooting extraction of plants for soil water in residue plots versus shallower rooting and extraction in disced plots. 2025 was evidenced by higher irrigation, lower WUE. Use of sprinklers to supply water in the study, either rotor or overhead linear move, provided some irrigation lessons in the endeavor to limit water deficit and provide effective watering. Shorter, more frequent irrigation sets were found to be more effective to overcome the lower soil water infiltration rate of silty clay loam approximately 6.1 mm hr^{-1}. Rotor sprinkler watering sets averaging 11.2 mm hr^{-1}, can easily overwhelm the infiltration capacity of fine texture soils as evidenced in spring of 2025, even though the soil profile was mostly empty at the time.

Soil texture results from the 20 cm depth indicated sandy clay or sandy clay loam in 64% of study plots, which was unexpected. The three highest yielding plots of the study occurred in 2024 on residue plots which had clay or clay loam soil textures, while the lowest yields of the study also simultaneously occurred on disced plots which all had sandy clay or sandy clay loam soil textures in the first 20 cm. Disced soils with a higher sand proportion in the upper 20 cm horizon of soil may have had greater water deficit due to less water holding capacity and less soil water moderation from cereal residue on the soil surface, creating an outsized negative effect on yield compared to winter peas planted in residue which had clay or clay loam texture at 20 cm. In 2025, although 71% of plots in 2025 had sandy clay loam soil texture at 20 cm no such effects were discernible perhaps because of higher overall irrigation volume of both residue and disc plots.

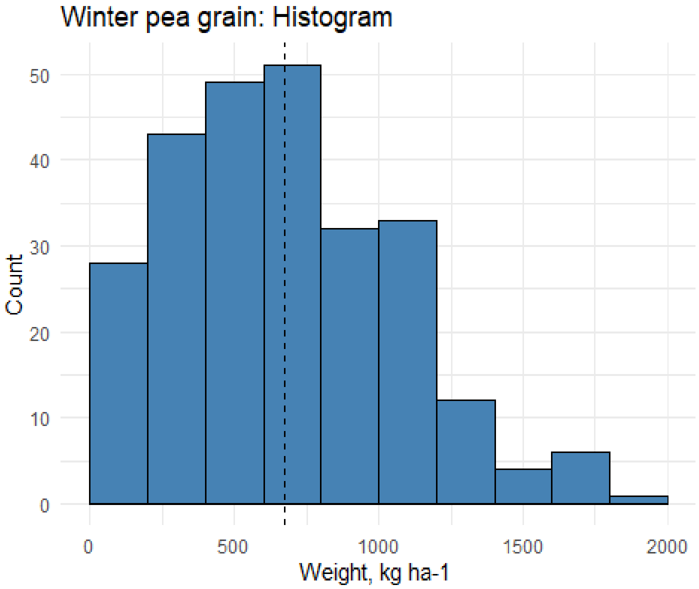
Economics of Winter Peas

The economics of incorporating winter peas into a continuous wheat rotation presented negative estimated profits in the enterprise budget, in both years of the study. In short, at this time, growing winter peas for edible grain was not profitable as a sole, stand-alone agricultural enterprise. Partial budget results also indicated a significant economic loss when edible winter peas were added to a continuous wheat rotation. If factors such as market demand increase of winter peas due to food manufacturing interest were coupled with a farm gate price (FGP) increase, sensitivity analysis suggests a potential sharp change (Table 13) in profits could take place. If average yield exceeded 2,497 kg ha^{-1}, the break-even yield amount calculated in this study, coupled with a reasonable increase in market price (e.g., FGP + 40%) due to use of peas as a protein substitute in food manufacturing, could result in greater economic returns for farmers.

Yield Patterns

This study has shown that planting winter peas into triticale or winter wheat cereal residue, though lacking conclusive evidence of significantly improving WUE, can improve overall yield. Using no-till approaches in a crop rotation that has winter peas following cereals helps reduce tillage costs and may help farmers transition into growing different cereals such as winter barley paired with a legume versus continuous wheat. Grain yields were more variable in disc plots as compared to residue plots as evidenced by the QQ plot (Figure 1, p. 24) at lower and upper values in 2024 and upper values in 2025, whereas residue plots followed the theoretical trendline much more closely. Overall, winter pea grain yield indicated a right skew in the constructed histogram (Figure 6).

Figure 6. Histogram, 2024-2025 of subplot winter pea grain yield. The dashed line is the sample mean of 675 kg ha^{-1}, bin-width = 200 kg ha^{-1} .

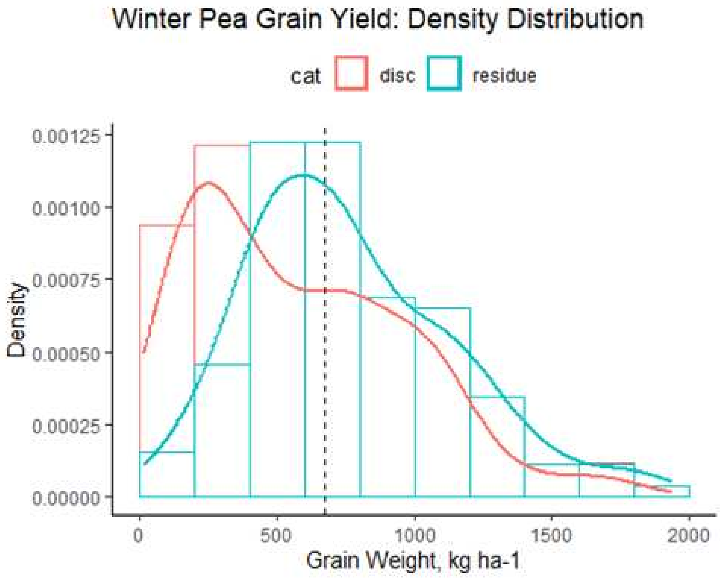


While the yield distribution pattern with right skew is reinforced, the differences in grain yield between disc and residue are better visualized in Figure 7. The higher grain yield of peas grown in residue averaged 767 kg ha^{-1} (n=131) while peas grown in disced triticale or wheat yielded 580 kg ha^{-1} (n=128) winter pea grain.

Future Research

There is evidence to suggest further studies of cereal residue effects on winter peas are merited. For example, the effect of irrigation water leasing programs such as the Colorado Water Conservation Board (CWCB), Collaborative Water Sharing Agreements (CWSA), have farmers lease their irrigation shares while keeping land fallow to conserve irrigation water for downstream usage in other parts of the Colorado river basin (CWCB, 2025). Farmers may earn $509 per acre-foot of water (CWCB, 2025). Fallow fields, with no minimal crop cover, often result in weed infestation. Recent research at WCRC-GV has indicated that winter peas can be planted in fall on furrow irrigation, watered, overwinter and then grow until at least May 1st as a cover crop with only natural precipitation, allowing farmers to lease water shares yet retain valuable soil cover and store N credits for future plant use.

Figure 7. 2024-2025 Winter Pea Grain Density Distribution.



The experiment indicated winter peas benefit from cereal straw residue and irrigation water to increase average grain yield over winter peas irrigated and planted in tandem disc harrow conditions. Although the study measured ET rates for winter peas in both residue and disced environments, it did not attempt to determine the ratio or partitioning of winter pea transpiration to evaporation. Moderation of soil moisture conditions by planting winter peas into no-till cereal straw may increase transpiration of pea plants, reduce evaporation losses and support higher average grain yield versus winter peas planted into tandem disc harrow conditions.

The study planting rate of 68 kg ha^{-1} may be considered a minimum rate. Studies in the future might examine the effect that higher seeding rates have on grain yield, water use efficiency, and economic return. Planting rates of 80, 90, 100 kg ha^{-1} with adequate irrigation water and residue cover could result in denser stands of peas with higher yields.

Future research might also examine whether cereal residue environments retain greater soil moisture over soils with tillage, thereby minimizing the yield limiting effects of photorespiration in dry peas. Photorespiration is the detrimental metabolic process of the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (RUBISCO) attaching to oxygen instead of carbon dioxide, which begins in the chloroplast. Heat, lack of humidity, light intensity and lack of adequate soil moisture contribute to stomata staying closed and the buildup of oxygen in the plant cell. Trapped oxygen and the limited input of carbon dioxide, force RUBISCO to spend more time processing oxygen instead of carbon dioxide. Photorespiration can occur while photosynthesis simultaneously takes place in the Calvin Cycle but results in lower photosynthesis efficiency. Photorespiration also creates the phytotoxic cellular compound Phosphoglycolate (2PG) which lowers crop yield by limiting enzymatic activity of RUBISCO.

Phosphoglycolate phosphatase (PGLP) is an enzyme in plant cells that breaks down the compound 2PG. Until recently PGLP activity was expensive and time consuming to measure in plants with either mass spectrometry or nuclear magnetic resonance methods. Recently a 96 well microplate assay to indicate the level of photorespiration in photosynthetic plant tissue was developed and offers a lower cost per test and high throughput potential (Roze et al., 2024). The high throughput potential of the microplate enzymatic test may allow for greater sampling potential and increase statistical power for randomized complete block design (RCBD) designs which could measure photorespiration in strips of winter peas or other legumes planted in cereal straw versus winter peas planted in a tillage control. If winter peas show reduced PGLP concentration when planted in cereal stem environments versus a tillage control, photosynthesis efficiency will improve resulting in higher grain yield and more efficient use of precious soil water.

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LIST OF ABBREVIATIONS

ATV-all-terrain-vehicle
AWC-available water holding capacity
CRF-capital recovery factor
C-Celsius
CFU-colony forming unit
cm-centimeter
CWCB-Colorado Water Conservation Board
CWUE-crop water use efficiency
CWSA-Collaborative Water Sharing Agreement
DP-deep percolation
DPH-depreciation per hour
ET-evapotranspiration
FGP-farm gate price
GPH-gallons per hour
ha-hectare
JD-John Deere
K-potassium
kg-kilogram
kg ha mm- kilograms per hectare per millimeter
MAD-management allowable depletion
m-meter
mg-milligram
MAP-monoammonium phosphate fertilizer, 11-52-0
N-nitrogen
NWS-National Weather Service

NRCS-Natural Resources Conservation Service

OM-organic matter

P-phosphorous

PTO-power take-off

PWP-permanent wilting point

PVC-polyvinyl chloride

RCBD-randomized complete block design

RO-runoff

TIH-taxes, insurance, and housing

USDA-U.S. Department of Agriculture

VWC-volumetric water content

WCRC-GV-Western Colorado Research Center/Grand Valley

WUE-water use efficiency

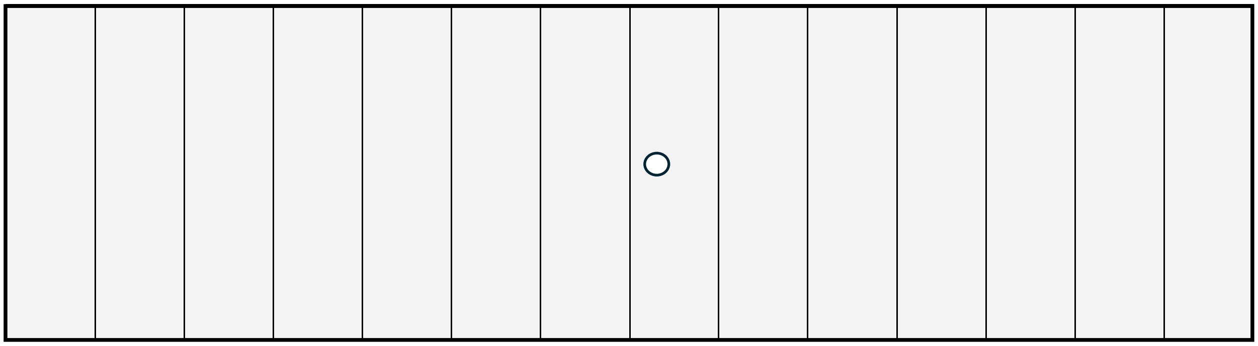
WP-winter pea

WW-winter wheat

APPENDIX

Appendix A. Neutron Probe Location

The bold line below represents the perimeter of a field plot while the column lines represent harvest subplot passes of the harvest combine within the plot. Represented by a circle, neutron probe tubes were placed near the center of each plot by measuring tape in an "X" pattern from cross corners.



In 2025, in addition to the centrally located probe tubes in each plot, two more probe tube locations were added to each plot away from the plot edges, in areas with good visual plant density.