Crop rotation influences yield more than soil quality at a semiarid location

Kent McVay, Qasim A. Khan

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Crop Rotation Influences Yield more than Soil Quality at a Semiarid Location

Core ideas

1. Rotations with fallow or a cover crop prior to winter wheat produced similar yield as winter wheat-fallow.
2. Soil water extraction during grain fill periods for camelina, lentil, and pea was limited to the top 55 cm of soil.
3. Fallow provides a greater grain yield benefit to winter wheat than to pea.
4. Particulate organic matter was greater in rotations with cropping intensity of 1.00 compared to 0.67.

ABSTRACT

Winter wheat (*Triticum aestivum* L.) (W) is often rotated with fallow (F) in semiarid regions to conserve soil moisture and minimize crop failure. We hypothesized that using direct seed systems coupled with intensified and more diverse crop rotations would produce an equivalent or greater annualized grain yield than a traditional winter wheat-fallow (WF) system. Further, continuous cropping would lead to an accumulation of greater soil carbon than the traditional WF. A 6-year study was conducted to evaluate crop rotations which included pea (*Pisum sativum* L.), lentil (*Lens culinaris* Medik), lentil as a cover crop, spring wheat, or camelina (*Camelina sativa* (L.) *Crantz*) in rotation with winter wheat in 2- and 3-year rotations. Results of this study averaged over 6 years showed that increased cropping intensity (CI) produced annualized yield equal to that of WF provided either fallow or a cover crop rather than another grain crop was present prior to winter wheat. Soil quality indices showed particulate organic matter (POM) increased with rotations with greater CI (1.00 vs 0.67), although POM of these rotations was not different from WF.

Abbreviations: C, carbon; Ca, camelina; ET, evapotranspiration; GDD, growing degree day; F, fallow; L, lentil; cc, lentil as a cover crop; NPP, net primary productivity; P, dry pea; PSE, precipitation storage efficiency; POM, particulate organic matter; SOC, soil organic carbon; S, spring wheat; W, winter wheat;

INTRODUCTION

Cropping systems in the northern Great Plains semiarid region have traditionally included fallow periods of 9 to 14 months to accumulate soil moisture to reduce the risk of crop failure (Nielsen & Calderón, 2011). Although including fallow has achieved success using this metric, the practice had the unintended consequence of reducing soil organic carbon (SOC) and thus soil health when practiced over many decades (Janzen, 2001; Nielsen & Calderón, 2011; Peterson et al., 1998). Stored soil moisture can also be lost to uncontrolled weed growth. Prior to use of herbicides, weed control was accomplished with tillage. Before the development of direct seeding equipment tillage was necessary to prepare a seedbed. Tillage reduces residue levels at the soil surface which increases the risk of soil erosion (Huawei, P. et al., 2020). Under semiarid conditions, exposed soil at the surface was susceptible to wind erosion during the long fallow period. The long-term result of this system has been degradation of topsoil and pollution of waterways.

Conservation tillage systems were introduced in the U.S. in the 1940’s and by the 1970’s herbicides for chemical-fallow weed control without tillage were becoming a more common practice (Huggins & Reganold, 2008; USEPA, 2021). Adoption of these practices significantly reduced topsoil losses primarily because the soil surface remained protected by crop residue through the majority of the fallow period. One benefit of this practice in the northern Great Plains was greater retention of precipitation in the soil during fallow which led to greater yields for the following crop (Nielsen et al., 2005). Research on precipitation storage efficiency (PSE) in the fallow period (Farahani et al., 1998) showed that PSE was lowest during hot, dry summer periods and greater in shorter cool periods like fall and early spring. They compared PSE at planting time and showed PSE prior to planting winter wheat in mid- to late September was lowest (19%) but greater preceding corn (*Zea mays* L.) or sorghum (*Sorghum bicolor* L.

Moench) planting (36%) in mid-May, or preceding millet (*Panicum miliaceum* L.) or sorghum planting (43%) in early June. They concluded that gains in efficient use of precipitation came from cropping intensification which used soil water for transpiration that would otherwise be lost to evaporation. Theirs' and others' research In the U.S. Great Plains (Schlegel, et al., 2019; Neilsen et al., 2002; Peterson et al., 1996) led to adoption of intensified crop rotations of wheat-corn-fallow, or wheat-grain sorghum-fallow and other crops. In the northern portions of the region adoption of these conservation tillage practices allowed increased cropping intensity using spring crops like spring wheat, pea (*Pisum sativum* L.), lentil (*Lens culinaris* Medik.), canola (*Brassica napus* L.), and sunflower (*Helianthus annuus* L.) (Tanaka et al. 2007).

Crop intensification can be attained through the use of cover crops. A recent summary of cover crop research where mean annual precipitation was < 500 mm (Blanco-Canqui et al., 2021) indicated including cover crops provided many environmental benefits such as increased SOC, reduced water and wind erosion, lower nitrate leaching potential, and increased soil microbial biomass. They concluded the addition of cover crops did not always result in reduced grain yield of a following crop, although timely termination of cover crops was critical to retain soil water.

Crop intensification can lead to greater SOC as compared to WF due in part to greater annualized crop biomass returned to the soil following grain removal. Engel et al. (2017) in Bozeman, MT showed that intensified cropping systems that exceeded 7.0 Mg ha^{-1} yr^{-1} of net primary productivity (grain + straw; NPP) can lead to increased SOC. A summary paper by Liebig et al. (2009) used long-term experiments from the U.S. Great Plains region to conclude that management practices capable of either increasing SOC or mitigating SOC loss included adoption of direct seeding, increased CI, and improved soil fertility. VandenBygaart et al. (2003) compiled data from 62 studies which showed higher frequency of fallow resulted in a lower potential to increase SOC regardless of tillage treatment, especially in the drier areas. They also showed that legume green manures or rotations of hay production appeared effective in increasing SOC. Campbell & Zenter (1993) showed replacing wheat with flax (*Linum usitatissimum* L.) in a crop-fallow system resulted in lower SOC and suggested it was due to lower productivity compared to wheat, higher nitrate leaching, and loss of flax straw by wind.

Changes in SOC can take many years to occur and differences may not be measurable under short-term management studies. Soil POM is a fraction of total SOC quantified through a physical separation based on size. It is considered plant material most recently added to and not yet associated with soil clay; therefore, POM is considered more reflective of recent soil management impacts including tillage and crop rotation as shown by Cates et al. (2016) in Wisconsin.

Dryland farming practices have changed through the years to include greater use of conservation tillage, direct seed systems, and intensified production, yet a significant proportion of cropland acreage remains fallowed in areas of the northern U.S. Great Plains. For example, over 1 million hectares were fallowed in Montana in 2021 (USDA FSA, 2021). Producers remain hesitant to adopt practices that have not been shown to work locally, yet there are some proven alternative crop options available in Montana. Pulse crops like pea and lentil currently occupy more than 400,000 ha annually in Montana (USDA FSA, 2021). Camelina hectarage remains low (< 5000 ha) but has been shown in research trials to be a promising crop for this region (Obour et al., 2018).

We hypothesized that direct seed systems coupled with intensified and diversified crop rotations would produce an equivalent or greater annualized grain yield than the traditional WF dryland cropping system. Further, intensified cropping would lead to an accumulation of greater

POM than the traditional WF following several years. Our objective was to establish a series of crop rotations of increasing CI to quantify annualized grain yield over time. Soils were evaluated at the end of the trial period for changes in SOC and other quality parameters.

MATERIALS AND METHODS

A 6-yr field study was conducted under dryland conditions from 2008 to 2014 at the Southern Agricultural Research Center, Montana State University, near Huntley, MT (45°55′N, 108°15′ W). The study spanned an area of two similar soil types; a Lohmiller silty clay loam (fine, smectitic, calcareous, mesic Torrertic Ustifluvents) and a Thurlow clay loam (fine, smectitic, mesic Torrertic Haplustalfs) with slopes $< 1.0\%$ and soil depth to 1.5 m.

The study design was a randomized complete block with 4 replications. Individual plot size was approximately 9 m by 27 m. The experimental treatment was crop rotation using a two- or three-crop rotation of winter wheat, fallow, spring wheat (S), pea (P), camelina (Ca), lentil grain (L) or lentil as a cover crop (cc). The result was seven rotations (Table 1) with all crops of each rotation included each year (20 individual plots per replication). All crops were established from 2008 – 2011 using a disc drill (John Deere 752, Illinois, USA) with row spacing of 15 cm, and from 2012 – 2014 using a direct seed air drill (SeedMaster, Saskatchewan, Canada) with a row spacing of 28.5 cm. in a no-tillage system.

Data from 2009 represents the first year of rotation after initial crop establishment in 2008 (fall 2007 for winter wheat). Cropping intensity was calculated as the number of grain crops divided by the number of years in a rotation, and ranged from 0.50 (WF) to 1.00 (WSCa). The lentil cover crop was terminated at flowering (approximately half of a full season crop), consequently the WScc treatment was assigned a CI of 0.83.

Crop management followed local recommendations for seeding rates, seeding dates, herbicide and fertilizer applications (Table 2). Legume crops were inoculated with the rhizobium inoculant (*Rhizobium leguminosarum biovar viceae*) (N Dure). The field was sprayed with glyphosate (N-(phosphonomethyl)glycine3) prior to planting each growing season to control emerged weeds. Pea and lentil plots were sprayed with pendimethalin (N-(1-ethylpropyl)-2,6-dinitro-3,4-xylidine) before planting each year. Lentil cover crop was terminated at flowering stage with a tank-mix solution of glyphosate plus bentazon (3-1-melhylethyl)-1H-2,1,3-benzothiadiazin-4 (3H)-one 2.2-dioxide). Broadleaf weed control in wheat was attained with post applications of bromoxynil (3,5-Dibromo-4-hydroxybenzonitrile) plus MCPA (2-methyl-4-chlorophenoxyacetic acid) at late tillering stage. Prior to termination, biomass was estimated by clipping 2 m of row which was weighed after drying at 36 °C until weight was stable. At maturity, yield of grain crops was estimated using a small-plot combine (Wintersteiger, Salt Lake City, UT) to harvest a single 1.4 m wide strip (4 rows) through each plot. The remaining crop grain in each plot was removed using a large field combine (Case International Harvester, Wisconsin, USA) which spread straw and chaff within each plot. The harvested seed was weighed for yield determination and grain yield was adjusted to moisture content of 13% for wheat and 10 % for pea, camelina and lentil. Moisture and test weight were determined on all grain using a Dickey-john GAC 2100 (Minneapolis, MN). Grain protein content was determined on whole grain using a Perten Diode Array DA 7200 near-infrared reflectance analyzer (Perten Instruments North America, Springfield, IL, http://www.perten.com).

Soil samples were collected in the fall of 2014 using a 5 cm diameter soil core sampler (AMS, American Falls, ID) at depths of 0 to 7.5 cm and 7.5 to 15 cm from approximately eight locations in those plots of each treatment returning to winter wheat. Two cores from each depth were used for bulk density, the rest were combined by depth for further analysis. Bulk density was determined on intact cores after drying at 105 °C using the core method (Grossman & Reinsch, 2002). Water holding capacity and chemical analysis were determined after samples were air dried and ground to pass a 2 mm screen. Water holding capacity was calculated as the difference in volumetric water content between wilting point (1.5 MPa) and field capacity (0.03 MPa) using a pressure plate extractor (Topp & Ferre, 2002). Soil organic carbon was determined as the difference between total C by direct combustion using a LECO CHN-2000 (LECO Corp., St. Joseph, MI) and inorganic C determined using a modified pressure-calcimeter method (Sherrod et al., 2002). Soil organic carbon was corrected to a mass basis using bulk density values for each sample depth.

Soil POM was determined on air-dried soils following the procedure of Cambardella et al. (2001) with the following modifications. A 25 g air-dried subsample was dispersed with 100 mL of sodium hexametaphosphate (50 g L^{-1}) in a 250 mL erlenmeyer flask on a reciprocating shaker for 4 hours. The soil suspension was then passed through a stack of 250 (macro fraction) and 53 (micro fraction) micron screens until water ran clean. Residual debris was transferred with minimal water into 100 mL beakers and evaporated at 60 °C overnight. Dried samples were then transferred to ceramic vials and placed in a muffle furnace at 450 °C for 6 hours. Soil POM was calculated as the percent mass loss multiplied by the bulk density of the sample depth and presented on a hectare basis.

Soil water was measured at the beginning and end of June of 2009, 2010, and 2012 to compare soil water use of different crop species. This time period was chosen as it coincided with flowering and grain fill growth stages of the crops in this study which is typically the peak crop water. Water content of the surface 0 to 15 cm depth was determined using a HydroSense soil water measurement system CS620 (Campbell Scientific, Utah, USA). Deeper soil water content was determined in 0.2 m increments to 1.15 m depth using a neutron probe (CPN Hydroprobe Model 503DR, CPN International, Concord, CA). Relative counts were converted to volumetric water content using a local calibration for each depth increment. Total water used by crops was estimated as the sum of precipitation for the period plus the net change in soil water content to 1.15 m. Daily evapotranspiration (ET) was estimated by dividing total water use by the number of days between initial and final measurements.

All grain yield results were corrected to standard moisture contents and were presented as annualized yield. Annualized yield was calculated as the sum of annual yields of all crops within a rotation divided by the number of crops within that rotation. Fallow and cover crop phases provide no grain yield.

Data was initially tested for normality by the Shaprio-Wilk test (PROC UNIVARIATE; SAS Institute, 2014). Bartlett's test was used to confirm the homogeneity of error variance between years and a combined analysis over years was conducted. Statistical analysis was performed using the PROC MIXED procedure in SAS 9.4 (SAS Institute, 2014). Crop rotation was considered as fixed effect with block as random effect within each year. When data were combined over years, crop rotation and year were considered fixed effects and block within year was considered as a random effect. Treatment means were separated using Fisher's F protected LSD test at $\alpha=0.05$. Single degree of freedom orthogonal contrast analysis was performed to compare the effect of CI on soil quality parameters.

RESULTS

Climate

Precipitation in southcentral Montana follows the summer rainfall pattern of the U.S. Great Plains with 33% of annual precipitation normally received from May 1 through June 30 at this location. Normal annual precipitation is 367 mm (Table 3). The majority of daily precipitation events are 15 mm and less with 5 mm being the most common daily accumulation (Fig. 1). These low daily precipitation amounts support the assumption of little to no runoff from precipitation. Precipitation is easily stored within the root zone for later use by crops where soils are deep as in this study. The years 2009-2011 and 2014 were wetter than average and 2012-2013 were drier than average for this study. Climate conditions in 2012 were not only dry, but were 2 °C hotter than normal during the growing season leading to much greater growing degree day (GDD) accumulation.

Grain Yield

In the wetter than normal years of 2009-10 the WScc rotation produced the most total grain (Table 4). Note that in these years pea was grown in place of lentil when grown for grain. In 2009 only WSCa yielded less than the other rotations. In 2011 the rotation PWF and WPF both yielded significantly less than the other crop rotations. In the drier year of 2012 WF provided the greatest annualized yield, while WSF and WPF which each had winter wheat following fallow, yielded less than WF but greater than all other treatments. The WSL treatment provided similar yield as WSF, with all other rotations yielding below 1.0 Mg ha^{-1}. The 2013 season was also drier than normal and the WF treatment yielded less than WPF and PWF. In 2013 those rotations with intensity >0.67 yielded the least. In 2014 where precipitation was again greater than normal the WSCa rotation provided the greatest annualized grain yield while PWF yielded the least. When averaged over all 6 years, mean annualized grain yield in WF was greater than PWF, WSL, and WSCa. The PWF rotation provided significantly less annualized grain yield than all other rotations.

For all crops grown, winter wheat yield contributed the greatest amount to annualized grain yield where fallow was practiced prior to winter wheat or where a cover crop was included (Fig. 2). Winter wheat produced about 50% of the annualized grain yield under continuous crop and the PWF rotation.

Soil Water Use

During the month of June, spring wheat, winter wheat, and lentil extracted the most soil water with spring wheat extracting significantly more than camelina and pea (Tables 5 and 6). Winter wheat used more soil water from the 75 to 95 cm depth than all other crops. Pea, lentil, and camelina removed small volumes of soil water at depths below 75 cm and significantly less than winter and spring wheat in the 55 to 75 cm depth. Differences in soil water extraction from the 0 to 15 cm depth although significant were small; winter wheat and camelina removed the least amount of soil water from this depth. Differences in extraction at this surface zone were complex due to the dynamic nature of precipitation events which occurred while soil water was being extracted by crops. Spring wheat consumed the greatest total amount of soil water during June (Table 5). Winter wheat and lentil consumed similar amounts while pea and camelina consumed the least amount of total available soil water. Differences in total soil water use were mirrored by daily ET estimates for the period.

Soil Quality

Seven years following the establishment of this study soils were sampled and evaluated for soil quality. Soil bulk density values differed by depth (P=0.001, Data not shown) but not by rotation (P=0.2271, Data not shown). The 0 to 7.5 cm depth averaged 1.17 Mg m^{-3} where as the 7.5 to 15 cm depth averaged 1.51 Mg m^{-3}. The average water holding capacity for the 0 to 7.5 cm depth was 0.163 m^3 m^{-3}, and was 0.203 m^3 m^{-3} for the 7.5 to 15 cm depth. No statistical difference in water holding capacity due to crop rotation was found. No differences in total C, inorganic C or SOC were found due to cropping rotation. Soil organic C averaged 893 Mg ha^{-1} across all crop rotations in the 0 to 7.5 cm depth. Soil POM in the 0 to 7.5 cm depth was not different when analyzed across all rotations (Table 7). Contrast analysis using CI showed macro and total POM was significantly less for CI of 0.67 compared to CI of 1.00 (Table 7).

DISCUSSION

This study compared six alternatives to WF, considered the standard rainfed annual crop rotation for the region. The WF was the highest yielding system in the driest year (2012) of this six-year trial (Table 4). This result was similar to the findings of Lenssen et al. (2007) from a cropping study conducted during three drought years. The stability of WF in this study showed the importance of fallow in providing a safety net of stored soil water for crop production in a semiarid region (Nielsen & Calderón, 2011; Nielsen & Vigil, 2018). Positive crop response to fallow occurs when soil type and depth are adequate to store significant precipitation when seasonal precipitation is limited. Results from the other five seasons showed more intensive crop rotations could provide a greater or equal amount of annualized grain yield as the standard.

Especially promising was the WScc treatment where a cover crop replaced fallow. Only in the drought year of 2012 did this treatment yield less than WF (Table 4.).

Rosenzweig et al., (2018) showed higher annualized yield was correlated with higher CI but like Nielsen, Vigil, et al., (2016) our results do not follow these trends (Table 4). The lack of a positive response to CI may be a function of soil type, crop choice or rotation, or the environmental conditions in this region including low intensity precipitation and short and cool growing seasons (Table 3, Fig. 1). This study did not include warm season crops like corn or grain sorghum as have been included in the central Great Plains where annualized yield was correlated with CI (Rosenweig et al., 2018). Shorter growing seasons and risk of early frost in this region place a greater risk on growing warm season crops. Adding a lower yielding cool-season crop like lentil and camelina increased intensity, but contributed less to overall annualized yield than winter wheat (Fig. 2).

Crop rotation was important. When WPF was compared to WFP, having fallow prior to winter wheat provided significantly more annualized yield in 3 out of 6 years and in the overall means (Table 4). When winter wheat followed fallow in this rotation, annualized winter wheat yields were 0.5 Mg ha^{-1} greater than when following pea (Fig. 2). Pea also benefitted from a preceding fallow but to a lesser extent. Annualized pea yield in WFP was 0.83 Mg ha^{-1} which was significantly greater than 0.69 Mg ha^{-1} in WPF (P=0.03) (Fig. 2). This was primarily attributed to the ability of wheat to access deeper soil water than pea (Table 5), but could also be due to greater water use efficiency of winter wheat compared to pea. Adding a cover crop in place of fallow as in WScc compared to WSF reduced annualized yield significantly in only 1 of 6 years and overall mean annualized yields of these rotations did not differ (Table 4). Nielsen, Lyon, et al. (2016) summarized over 100 site years of cover crop studies primarily from the U.S.

Great Plains which showed mostly negative impacts of cover crops on subsequent grain yield. In semiarid central and southern Great Plains region growing legume cover crops reduced subsequent wheat yield in wheat-fallow systems (Schlegel & Havlin, 1997). This may be due to greater evapotranspiration in the central compared to the northern Great Plains. Legume cover crops however showed promise in the northern Great Plains including Montana and had limited or no wheat yield reduction by a prior legume cover crop (Khakbazan et al., 2020; Burgess et al., 2014; Miller et al., 2006). The impact of lentil grown for grain (WSL) as compared to lentil managed as a cover crop (WScc) was best seen by differences in winter wheat yield in Fig. 2. It is apparent that lentil grown for grain reduced yield of a following crop of winter wheat as compared to growing lentil as a cover crop when terminated prior to grain fill. Total annualized grain yield was not significantly impacted, but the annualized grain yield contribution shifted from winter wheat to lentil when lentil was not terminated. Yield trends like these coupled with market prices can inform producers on whether to terminate a crop like lentil or allow it to finish as grain. Camelina was the lowest yielding species in this study (Fig. 2).

Soil water extraction indicated wheat accessed deeper soil water than all other crops with winter wheat extracting soil water to 115 cm while spring wheat was limited to 95 cm during June of the cropping season (Table 5). Lentil extracted soil water only to 75 cm (Table 5) but removed in total as much soil water as wheat (Table 6) by removing more from the shallower soil depths. Camelina appeared to access soil water similar to pea. Miller & Holmes (2012) showed similar soil water use for pulse crops and wheat as in this study. Gesch & Johnson (2015) showed 80% of camelina root density was in the 0 to 30 cm soil depth in a double-crop system in northcentral U.S.

Soil quality measures showed little change over the course of this 6-year study. No differences in SOC were detected to 15 cm depth which is in contrast to what was found 5 years after cover crops replaced fallow in a silt loam soil in western Kansas where SOC increased (Blanco-Canqui et al., 2013). Greater macro and total POM were detected in the 0 to 7.5 cm depth for rotations with CI of 1.00 over those with CI of 0.67 which indicated a potential for greater carbon accumulation with continuous cropped systems over those with fallow, although POM of WF was not different from any other treatment or combination of treatments evaluated (Table 7). Sherrod et al. (2005) found similar results for POM in Colorado after a 12-year dryland crop rotation study. Bowman et al. (1999) found more substantial increases in both SOC and POM after 3 and 6 years of increased CI although their SOC levels were lower than those in this study, and conducted on soils of lower clay content. In this study the stability of POM in WF may be related to the high grain yield and associated high level of biomass in this standard system over 7 years including the dry year of 2012. Engel et al. (2017) suggested that 7.0 Mg ha^{-1} yr^{-1} NPP was necessary to affect change in SOC and the NRCS (2011) conservation practice standard for cover crops recommends a minimum of 4480 kg ha^{-1} to achieve beneficial SOC effects. Net primary productivity was not measured in this study but with maximum annualized grain yield of 2.5 Mg ha^{-1}, it is unlikely that either threshold was reached. More time in these or similar rotations or inclusion of forage or perennial crops in rotation with annual cropping may be required to achieve a significant increase in SOC in this environment (Nielsen, Vigil, et al., 2016). Sherrod et al., 2005 showed perennial grass treatments resulted in twice the amount of POM as WF after 12 years.

Results of this study averaged over 6 years showed that increased CI produced annualized yield equal to that of WF provided either fallow or a cover crop rather than another grain crop was present prior to winter wheat. Soil quality indices showed POM was higher in the 0 to 7.5-cm depth with rotations with greater CI (1.00 vs 0.67), although POM of either group was not different from WF. The WF rotation remains a very competitive crop production choice for growers aiming to maximize annualized grain yield in this semiarid environment.

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Table 1. Crop rotation treatments and the associated cropping intensity value used for the study in southcentral Montana.

Crop Rotation	Abbreviation	CI[a]
Winter wheat – fallow	WF	0.50
Winter wheat – spring wheat – fallow	WSF	0.67
Winter wheat – pea – fallow	WPF	0.67
Winter wheat – fallow – pea	WFP	0.67
Winter wheat – spring wheat – lentil cover	WScc	0.83
Winter wheat – spring wheat – lentil	WSL	1.00
Winter wheat – spring wheat – camelina	WSCa	1.00

[a] Cropping intensity (CI) is calculated as number of crops divided by number of years, the cover crop was terminated at flowering and considered as 0.50 of a full season crop.

Table 2. Target seeding rate, approximate planting date and planting depth over seven growing seasons (2008-2014) for all crops in southcentral Montana.

Crop	Planting Date	Planting depth	Seed rate	Nitrogen[a]
		cm	seeds m^{-2}	kg N ha^{-1}
Winter wheat	Sep 20 – Oct 20	5	129	200
Spring wheat	March 25 – April 20	4	188	140
Dry pea[b]	March 25 – April 20	5	86	0
Lentil[b]	March 25 – April 20	4	108	0
Camelina	March 20 – April 10	1.5	195	56

[a] Nitrogen fertilizer was urea broadcast after emergence and rates were reduced by total residual soil nitrate measured to 1-m depth each year.
[b] Seed were inoculated with rhizobium inoculant each year.

Table 3. Summary of climatic data for six years in southcentral Montana.

Year	Precipitation[a]	Temperature[b]	GDD[c]
	mm	°C	°C days
2009	427	12.6	2412
2010	411	14.0	2582
2011	491	14.1	2648
2012	199	15.9	2930
2013	315	13.6	2582
2014	475	13.1	2517
Trial mean	386	13.9	2612
2001-2020 mean	367	13.9	

[a] Summed from September of previous year through August
[b] Daily mean
[c] Growing degree days, summed from March through August for each growing season.

Table 4. Annualized total grain yield for each rotation in southcentral Montana. Treatments arranged in increasing cropping intensity from 0.50 to 1.00.

Crop Rotation	CI[a]	2009	2010	2011	2012	2013	2014	Mean
		———	———	———	Mg ha^{-1}	———	———	———
WF	0.50	3.1 b	3.0 b	2.8 a	2.1 a	1.5 c	2.6 b	2.5 a
WSF	0.67	3.1 b	3.2 b	2.7 a	1.5 bc	1.5 c	2.6 b	2.4 ab
WPF	0.67	3.0 b	3.1 b	2.3 b	1.7 b	2.3 a	2.2 bc	2.4 ab
PWF	0.67	2.4 bc	3.3 b	2.0 c	0.9 d	1.8 b	1.9 c	2.1 c
WScc[b]	0.83	3.4 a	3.9 a	2.8 a	0.5 e	1.2 cd	2.5 b	2.4 ab
WSL[c]	1.00	2.9 bc	3.2 b	2.8 a	1.4 c	1.0 d	2.5 b	2.3 b
WSCa	1.00	2.8 c	3.1 b	2.8 a	0.5 e	1.3 cd	3.1 a	2.3 b

[a] CI=cropping intensity

[b] Cover crop biomass averaged 2.4 kg ha^{-1} but was not included in annualized grain yield.

[c] Pea was planted in place of lentil in 2009 and 2010

W=winter wheat, F=fallow, S=spring wheat, P=dry pea, L=lentil, cc=lentil cover crop, Ca=camelina.

Mean values within a column followed by the same letter are not significantly different ($P<0.05$) using Fisher's F protected LSD.

Table 5. Soil water extraction for different crops and soil depths during June averaged over 2009, 2010, and 2012 in southcentral Montana.

Soil Depth[a]	Pea	Camelina	Lentil	Winter wheat	Spring wheat
—cm—	———	———	cm water	———	———
0-15	9 ab	7 b	11 a	4 c	10 a
15-35	18 ab	17 b	21 ab	17 b	23 a
35-55	16 b	16 b	28 a	17 b	27 a
55-75	6 b	9 b	5 b	16 ab	18 a
75-95	1 b	3 b	1 b	11 a	5 b
95-115	0 b	1 b	2 ab	5 a	1 b
0-115	51 b	54 b	70 ab	70 ab	85 a

[a] Soil depth increments (cm)

Mean values within each column followed by the same letter are not significantly different ($P < 0.05$) using Fisher's F protected LSD.

Table 6. Soil water use and estimated daily evapotranspiration during June averaged over 2009, 2010, and 2012 for different crops in southcentral Montana.

Crop	Total [a]	Evapotranspiration
	mm	mm day^{-1}
Pea	124 c	4.5 c
Camelina	127 c	4.6 c
Lentil	146 b	5.5 ab
Winter wheat	144 b	5.2 b
Spring wheat	170 a	6.0 a

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[a] Calculated as the change in soil water content to depth of 115 cm plus precipitation received over the period.

Mean values within each column followed by the same letter are not significantly different ($P < 0.05$) using Fisher's F protected LSD.

Table 7. Soil particulate organic matter fractions in the 0 to 7.5-cm soil depth following six years of various crop rotations in southcentral Montana.

Crop Rotation[a]	CI[b]	Macro[c]	Micro[d]	Total[e]
		Mg ha^{-1}		
WF	0.50	1.54	3.8	5.34
WSF	0.67	1.28	2.96	4.24
WPF	0.67	1.25	3.36	4.61
PWF	0.67	1.28	3.02	4.29
WScc	0.83	1.99	3.05	5.04
WSL	1.00	1.73	2.87	4.59
WSCa	1.00	2.70	3.98	6.68
		P Values for Contrast Analysis		
Contrast[f]	0.50 vs 0.67	0.5413	0.1027	0.1845
	0.50 vs 0.83	0.4056	0.1406	0.7265
	0.50 vs 1.00	0.1611	0.3818	0.6955
	0.67 vs 1.00	0.0132	0.3441	0.0351

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[a] W=winter wheat, F=fallow, S=spring wheat, P=dry pea, L=lentil, cc=lentil cover crop, Ca=camelina.

[b] CI=cropping intensity.

[c] Particulate matter sized from 250-µm to 2-mm.

[d] Particulate matter sized from 53 to 250-µm.

[e] Total = sum of macro plus micro.

[f] Treatments were combined by CI values for contrast analysis.

Figure 1. Daily precipitation histogram on an annual basis for the period of 2001-2020 in southcentral Montana.

Figure 2. Averaged annualized grain yield for each crop within a rotation from 2009-2014 in southcentral MT. Different lowercase letters above each column indicate total annualized yield among rotations are significantly different at $P<0.05$ using Fisher's F protected LSD. Different uppercase letters within columns indicate annualized winter wheat yield among rotations are significantly different at $P<0.05$ using Fisher's F protected LSD.

[a] W=winter wheat, F=fallow, S=spring wheat, P=dry pea, L=lentil, cc=lentil cover crop, Ca=camelina.

Figure 1.

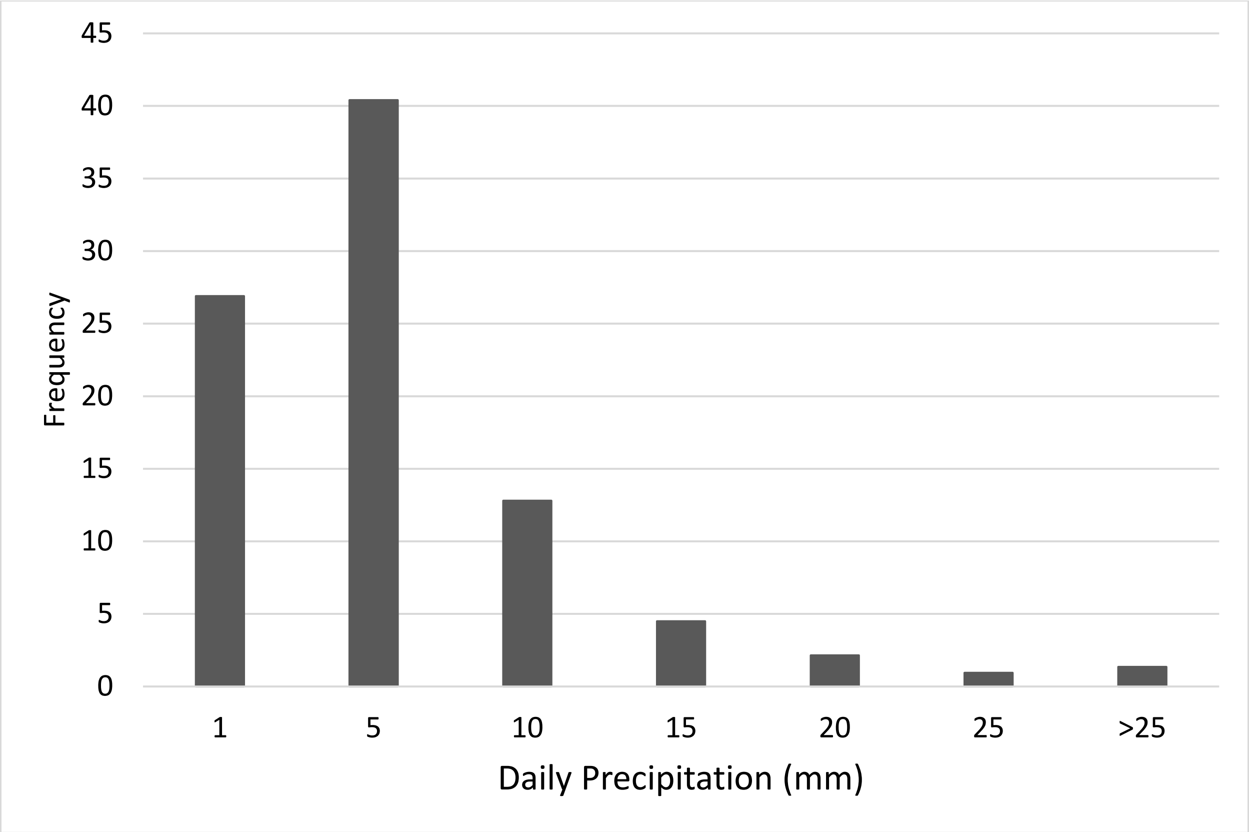
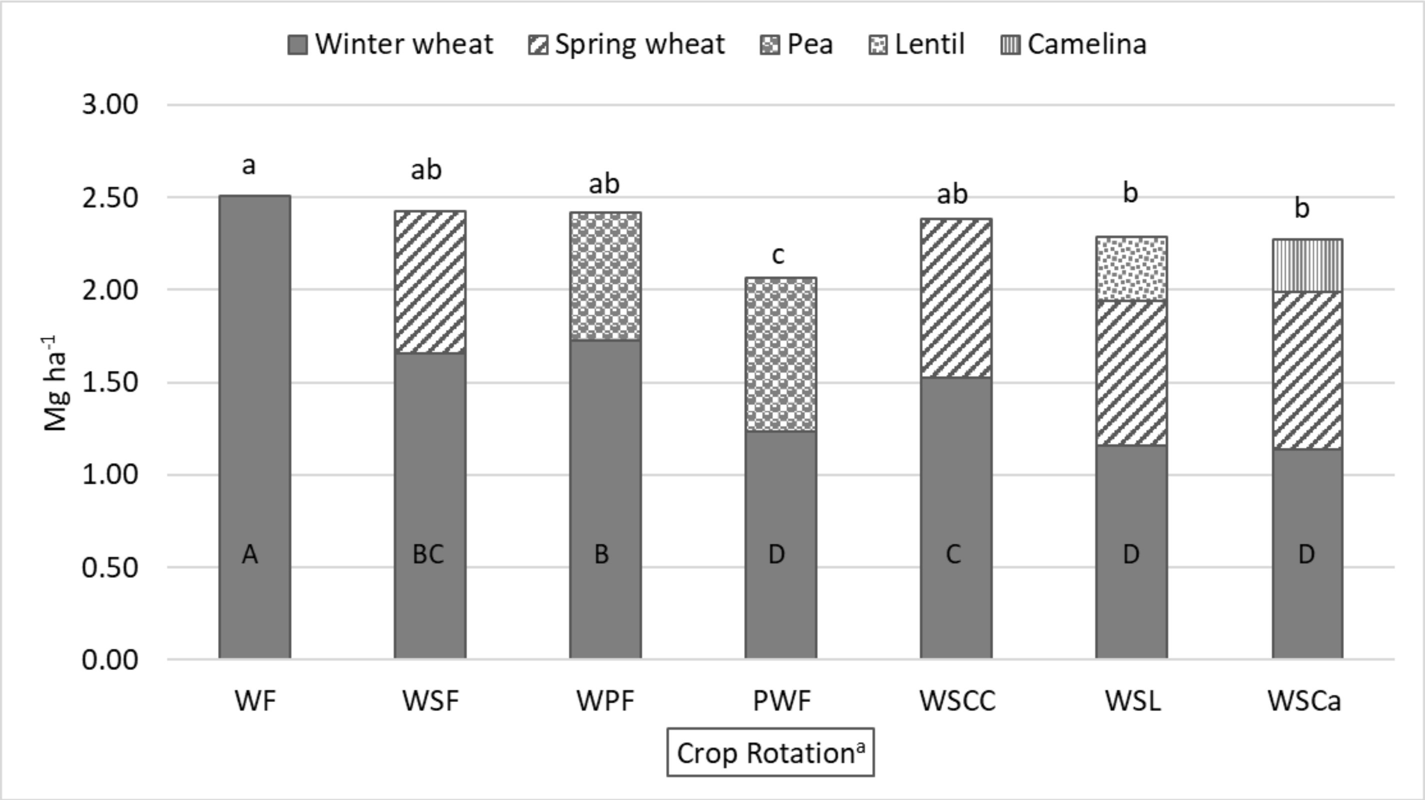


Figure 2.



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