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Soil Water Dynamics with Spring Camelina in a Three-Year Rotation in Washington's Winter Wheat–Fallow Region

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Camelina [*Camelina sativa* (L.) *Crantz*] of the Brassicaceae family is a short-season drought- and frost-tolerant oilseed. Camelina has been promoted as an alternative crop for the low-precipitation (<350 mm annually) Mediterranean-like climate region of the US inland Pacific Northwest, where a monoculture 2-yr winter wheat (*Triticum aestivum* L.) (WW)–summer fallow (SF) rotation is widely practiced. An 8-yr experiment was conducted to compare a 3-yr WW–camelina–SF rotation with the typical 2-yr WW–SF rotation to analyze the soil water dynamics of these two crop rotations. Growing spring-planted camelina reduced soil water content at the beginning of the fallow; this reduction resulted in an average of 21 mm less water at WW planting and a 170 kg ha^{-1} reduction in grain yield compared with WW–SF. We show that (i) the deep-rooted broadleaf weed Russian thistle (*Salsola tragus* L.) present in camelina most years was the most likely reason for greater in-crop soil water use than with WW–SF, and (ii) the limited camelina residue was probably responsible for greater evaporative loss during the spring to late summer segment of the fallow. We report the first findings from the Pacific Northwest drylands of greater water use by a cool-season spring crop versus WW and greater evaporative loss during the summer caused by lack of residue in a minimum-tillage SF comparison. Here, extending the crop rotation to include camelina was costly in terms of water use, surface soil residue cover, soil water storage during the fallow, and WW grain yield.

Abbreviations: SF, summer fallow; SW, spring wheat; WUE, water use efficiency; WW, winter wheat

Core Ideas

- **The soil water dynamics of 3-yr winter wheat–camelina–summer fallow and 2-yr winter wheat–summer fallow rotations were measured for 8 yr.**
- **At harvest, there was less soil water after camelina than after winter wheat in the 2-yr rotation.**
- **The water deficit persisted through the 13-mo fallow period and decreased the yield of 3-yr vs. 2-yr winter wheat.**
- **Increased cropping intensity may increase risk and variability in dry environments.**

Extended fallow is a management tool for improving the reliability and productivity of crops in climates where stored soil water is essential for reducing drought stress. In the Mediterranean-like climate (cool to cold wet winters and warm to hot dry summers) of the Pacific Northwest, a 2-yr WW–SF rotation is the dominant crop rotation in areas that receive < 350 mm of annual precipitation. Winter wheat and other winter crops such as winter pea (*Pisum sativum* L.), winter canola (*Brassica napus* L.), and winter triticale (× *Triticosecale schlanstedtense* Wittm.) need to be planted in late summer into moisture to achieve economically viable grain yields, which requires a summer fallow. Winter crops make efficient use of stored soil water and complete flowering and are well into grain filling before the onset of high air temperatures. Compared with WW, all spring-planted crops so far tested in the region are much more negatively impacted by spring drought and heat and have higher economic and yield variability (Juergens et al., 2004).

Precipitation soil water storage efficiencies (i.e., the percentage of water stored in the soil during the 13-mo fallow period) average around 30% (Wuest and Schillinger, 2011). Soil water storage efficiencies during the cool, wet winter months average about 65%. Evaporative water loss in SF occurs in the top 90 cm during the summer months. Deep soils and low precipitation result in incomplete recharging of

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soil water in the rooting zone almost every year. Despite this, the limited amount of soil water stored during the fallow year helps assure the establishment and deep rooting of WW to provide stable, albeit sometimes modest, grain yield if spring rain is lacking during grain filling.

The challenge in developing alternatives to WW–SF is to find crops that consistently produce a high value themselves or produce rotation benefits for WW. In theory, a spring crop might use some of the soil water that would otherwise evaporate in the summer months during the fallow to produce a crop that would more than pay for the cost of production and also provide a rotation benefit for the subsequent WW. Rotation benefits are likely to occur through improved grassy weed control (San Martín et al., 2019) or improvements in root health (Angus et al., 2001). If the alternative crop produces a profitable yield without extracting deeply stored soil water, this could result in improved overall water use efficiency (WUE).

Evaporation can dominate the top 40 cm of a soil profile during the fallow (Cabelguenne and Debaeke, 1998). Soil water stored deeper in the profile in dry climates can have a large effect on yield per mm of available water because it is not as subject to evaporation; this deep water is available later in the season during grain filling (French and Schultz, 1984) when it can be highly efficient at increasing yields (Schillinger et al., 2008). Therefore, a crop that does not deplete water from deep in the profile might work to extend the rotation to produce two crops in 3 yr, with only 1 yr of fallow to allow timely establishment of WW. For example, spring wheat (SW) grown in a 3-yr WW–SW–SF rotation consistently and significantly uses less soil water than WW in the 2-yr WW–SF rotation in east-central Washington (Schillinger, 2016) and much of this additional water remains in the soil profile at the end of the subsequent 13-mo fallow period in WW–SW–SF versus WW–SF.

In addition, rotation crops that improve the root health of the following WW are likely to allow more complete and deeper soil water extraction and increase grain yield. Soil water extraction limits for wheat can vary depending on the health of the crop (Angus et al., 2001), which in turn, depend on root health and water availability during crop development (Smiley and Machado, 2009). Therefore, there is likely to be a tradeoff among disease, nutrients, and water in the development of deep, effective roots in WW (Smiley et al., 2013).

Cool-season spring crops often use less water than WW in Mediterranean climates because heat units accumulate quickly in the spring and the time for root development is shortened. Research from other areas have indicated that many cool-season spring crops use similar amounts of water and to similar depths, whereas WW extracts water from deeper than the spring crops. In the semiarid Canadian prairie, spring canola depleted soil water in similar amounts and at similar depths as SW (about 120 cm), whereas WW extracted soil water from below 160 cm in dry years (Cutforth et al., 2013). However, in semiarid Montana (Miller and Holmes, 2012), camelina's water use and depth of water use was similar to that of spring canola, SW, and WW.

Stored soil water was repeatedly measured in a recent 8-yr dryland cropping system experiment that compared a 3-yr WW–spring camelina–SF rotation with a 2-yr WW–SF rotation. The agronomic results of that study were reported by Schillinger (2019). Susceptibility to wind erosion during the SF period in these two rotations was reported by Sharratt and Schillinger (2016). Here, we examine the patterns of soil water use and recharge to learn where potential improvements can and cannot be expected when seeking alternatives to the 2-yr WW–SF system.

MATERIALS AND METHODS

An 8-yr cropping system experiment was conducted from 2010 to 2017 at the Washington State University Dryland Research Station near Lind, WA. The objective was to compare the agronomic performance of a 3-yr WW–spring camelina–SF rotation to the 2-yr WW–SF rotation that is widely practiced by farmers throughout the region. Each rotation phase was represented each year, for a total of five plots in each of four replicate blocks. Plots measured 9 by 76 m. Only two of the years between 2010 and 2017 (2014 and 2015) experienced below-average precipitation for the location.

Precipitation was recorded at an official US National Weather Service recording site located <0.5 km from the experiment. Annual crop-year precipitation (1 September to 31 August in 2010 to 2017) averaged 281 mm (Fig. 1). The soil at the site is >180 cm deep and is a uniform Shano silt loam (coarse-silty, mixed, superactive, mesic, Xeric Haplocambids) with 10% clay, 51% silt, and 39% fine sand. These soils are very weakly aggregated, formed in deep deposits of loess.

The SF was a 13-mo period following WW or camelina harvest in July. Identical management practices and timings were used for SF in the 3-yr rotation following camelina and in the 2-yr rotation following WW. Weeds were controlled with herbicides [a.i. glyphosate (2-[phosphonomethylamino]acetic acid)] until mid- to late April, when fertilizer was applied and initial tillage at a depth of about 13 cm was performed using one pass of a low-disturbance undercutter sweep (Haybuster 3200 undercutter V-sweep, DuraTech Industries International Inc., Jamestown, ND). A rod weeder (a noninversion implement; Trashmaster, Coombs Manufacturing Co., Spokane, WA) was used once or twice as needed during late spring and summer at a depth of 10 cm to control weeds in SF. Winter wheat was planted into SF in both rotations in late August or early September. This SF system is considered a conservation tillage system because of the reliance on herbicides to delay tillage and minimize soil disturbance, and an emphasis on retaining surface residue. It has also been shown to maximize storage of precipitation while maintaining a moist seed zone below the tillage mulch layer for planting WW with deep-furrow drills (Papendick, 2004).

Camelina (cv. Calena) was planted directly into standing and undisturbed WW stubble in late February or early March. Full details on herbicides and equipment used, fertilizer rates, and other field-related operations for the experiment are reported in Schillinger (2019).

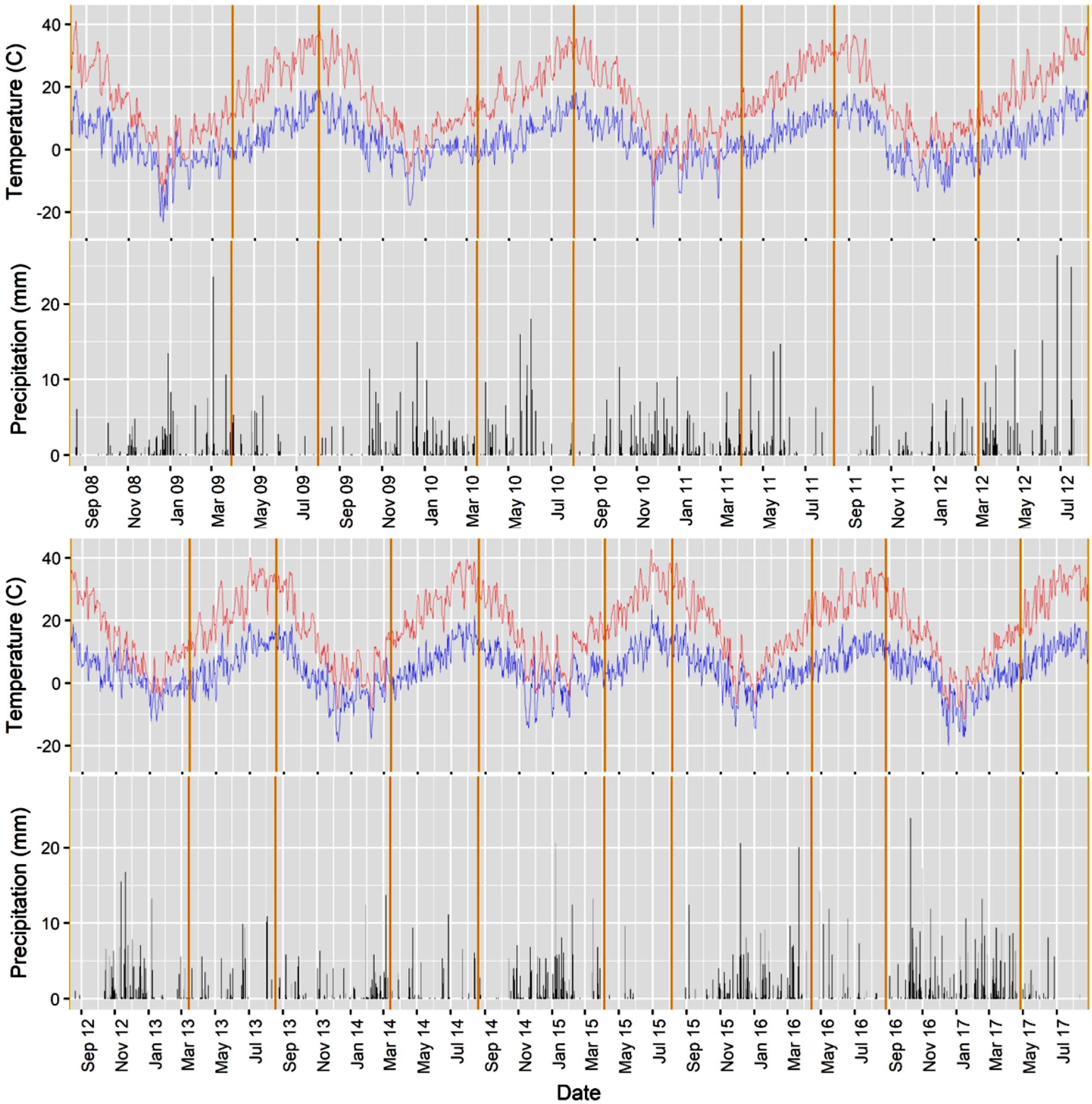

Fig. 1. Daily precipitation and maximum and minimum temperatures for 2008 to 2017. The vertical divisions mark sample dates.

Differences in weed pressure between the 2- and 3-yr rotations were observed and measured (Schillinger, 2019). Plots were kept essentially weed-free during the 13-mo SF period in both rotations. The introduction of camelina in the 3-yr rotation allowed for effective control of the grass weed downy brome (*Bromus tectorum* L.), but the lack of registered broadleaf herbicides for camelina caused Russian thistle to sometimes be a substantial problem in camelina, especially in the drier years. Russian thistle is a deep-rooted weed with a highly efficient C_4 photosynthetic pathway and is well known to extract water from deep in the soil profile (Beckie and Francis, 2009). In both rotations, the weed pressure was not considered extreme or even unusual for local production of WW and camelina. Controlling Russian thistle in spring crops, especially broadleaf crops, is difficult in this region and, for this study, the water use of the camelina crop and the weeds within it were considered inseparable. We note that elimination of spring broadleaf weeds would be expected to increase yield and decrease the water use of camelina; however, weed pressure during this study was considered normal for this crop in a dry, rainfed environment such as the Lind location.

Soil Water Measurements

Volumetric water content was measured in each plot twice a year with a neutron probe (CPN 503 Hydroprobe, InstroTek Inc., Raleigh, NC) for the 30- to 180-cm depth at 15-cm intervals, and gravimetric samples were taken for the 0- to 15- and 15- to 30-cm depths. Plots were sampled in early August after crop harvest or in late August before seeding WW. All plots were sampled yearly in late March. Late March is in the middle of the fallow period, in the middle of WW development phase, and during the seedling emergence phase for camelina. Soil samples at 15-cm intervals to 180 cm deep were taken from four locations in the experimental area for developing a water release curve. The water content vs. water potential curve was determined for each depth with a WP4C psychrometer (Decagon Devices, Pullman, WA).

Mulch Measurements

On 31 July 2015, the depth of tilled soil mulch was estimated from the average of 30 measurements across each fallow plot. Furthermore, soil from 0 to 10 cm from one plot of each treatment was sieved on a mechanical shaker to determine dry aggregate distribution. At the same time, samples of surface residue and large intact cores were collected for lysimeter measurements.

Lysimeter studies were conducted to investigate the possibility that differences in soil water were caused by differences in the properties and quantities of camelina residue versus WW residue or differences between the tilled soil mulch of the two systems. Two approaches were used. In the first approach, surface residue from the two treatments was collected and taken to the USDA Agricultural Research Service station near Pendleton, OR. The residues were applied to the surface of "bucket" lysimeters (Wuest, 2017) at dry rates of 150 and 300 g m^{-2} (1.5 and 3 Mg ha^{-1}). Weekly weight measurements were made from 13 Aug. 2015 to 20 Nov. 2015.

The lysimeters were made from standard polyethylene buckets designed to hold 26.5 L. The buckets were tapered. One bucket was placed into the ground, with the top 2 cm above the soil. This liner allowed another bucket to be inserted and maintained at normal soil temperatures while being easily removed for weighing. The bucket containing the soil had the top trimmed off so that the soil surface in the lysimeter was about 7 cm above the soil surface outside the lysimeter and the soil surface in the lysimeter was about 1 cm below the rim to prevent loss of soil or water out of the lysimeter while minimizing shading by the bucket rim.

To prevent wind from disturbing the surface residue, a thin monofilament net was tied over the top of each lysimeter. About once a week, the lysimeters were suspended from a load cell, pulled out of the liners with a block and tackle, and weighed to within 10 g or less. In this experiment, the lysimeters were filled with moist Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxerolls) packed at a density of 1.1 g cm^{-1} to within 13.5 cm of the top, and then a loose 12.5-cm layer of the same soil was placed on the surface to mimic a tilled layer of soil.

For the second approach, intact cores were taken directly from the plots at Lind on 16 July 2015 and 31 July 2015. Steel cylinders 20 cm in diameter, 30 cm tall, and with a 3-mm wall thickness were driven into the soil surface of the plots with a slide hammer. The surface soil in the plots had been tilled and was easy to penetrate, and the soil beneath the soil mulch was moist, so driving the cylinder only caused minimal core disturbance near the perimeter. The cylinder with the intact core inside was removed, the bottom was sealed with plastic and a support disk, and each cylinder was transported on a platform suspended by rubber cords to prevent vibration and shock from settling the soil. Soil mulch settling of about 1 cm was evident on the first sampling date but there was very minimal settling on the second date. These cores were placed in steel liners buried in the soil near Pendleton, OR, and weighed via the same methods as the bucket lysimeters. The cylinders were weighed weekly until 20 Nov. 2015.

Table 1. Orthogonal contrasts of differences in soil water (mm) measured: in August after the harvest of winter wheat (WW) or camelina, in late March during the fallow, in August before WW planting, in late March in actively growing WW, and in August after WW harvest. The table shows differences in the 2-yr WW–SF rotation minus the 3-yr WW–camelina–SF rotation.

Orthogonal contrast	0–45 cm	60–105 cm	120–180 cm	0–180 cm
		mm difference		
1. Harvest, 2-yr WW vs. camelina	1.4†	3.6**	8.1**	16.2***
2. Fallow spring, 2-yr vs. 3-yr	–1.2	2.7	7.9*	12.2*
3. WW planting, 2-yr vs. 3-yr	1.7	3.2*	13.1***	21.2***
4. WW spring, 2-yr vs. 3-yr	1.5	3.3	7.6*	14.8*
5. WW harvest, 2-yr vs. 3-yr	0.2	–0.3	0.3	0.4

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Positive numbers mean more water in the 2-yr rotation. Data are means of 6 yr and four replicate plots each year.

Analysis

The field experiment at Lind was conducted for 10 yr. It took 2 yr for a full cycle of the 3-yr rotation to produce a WW crop that was truly "in rotation"; thus Schillinger (2019) reported this as an 8-yr experiment conducted from 2010–2017. In 2 yr (2013 and 2015), newly emerged camelina seedlings were killed by a combination of frost and dry surface soil, so weeds were controlled and these plots were maintained as "double" fallow (i.e., two back-to-back years of fallow). For that reason, data from the 2013 to 2015 and 2015 to 2017 3-yr cycles were removed from the main analysis. This left a total of 6 yr where soil moisture profiles from the 3-yr and 2-yr rotations could be compared directly.

As well as analyzing soil water in the total rooting depth, we partitioned the soil profile into three depth intervals for analysis on the basis of the most prominent inflection points. Two gaps were left between the three intervals to increase the separation of effects. The four sets of intervals where water content was totaled for analysis were: (i) the entire profile (0–180 cm), (ii) surface (0–45 cm), (iii) mid-root depth (60–105 cm), and (iv) the deep root zone (120–180 cm).

Differences in soil water at each depth interval were tested via a linear mixed model (Bates et al., 2015) with the year and plot replicates as random effects and the rotation × phase within the rotation interaction as fixed effects. Preplanned effects were tested using orthogonal contrasts.

RESULTS

At the time of WW planting following a 13-mo fallow period, the 3-yr rotation consistently had less stored soil water than the 2-yr rotation (Table 1). The difference in soil water between the two systems started at camelina harvest, where camelina, in combination with Russian thistle, consistently depleted more soil water than WW in the 2-yr rotation (Table 1, Fig. 2). This deficit relative to the 2-yr system remained at the time of the late March soil water measurement taken during the fallow, was present at time of WW planting in late summer, and was still statistically significant the following spring (Table 1). By WW harvest the following July, the 2- and 3-yr rotations had nearly identical soil water profiles, although WW grain yield was significantly greater ($p < 0.05$) by an average of 170 kg ha^{-1} in the 2- vs. 3-yr rotation (Schillinger, 2019).

Patterns of soil water recharging can be seen in Fig. 2. The winter after WW or camelina harvest restored some water to the upper profile, mostly to above 135 cm, as shown in the measurements made in late March of the fallow year. Water infiltrated deeper in the profile from late March to late summer. This downward water movement was from redistribution of the stored water gained during the winter. More net soil water additions were seen the following spring during the WW phase. It is evident that this soil profile can hold more water than is typically supplied in one winter following harvest.

Water profiles at WW harvest were consistently the same year-to-year between the two rotations. For easier comparison between this dataset and those on different soil types, the harvest soil water content profiles from Fig. 2 have been converted to soil water potential in Fig. 3 according to the soil water characteristic curves generated from soil samples from the plot area.

There were no substantial or statistically significant differences in evaporation or water gain after rainfall events between camelina and WW surface residues placed on Walla Walla soil in the bucket lysimeters (data not shown). There were also no differences in evaporation between SF mulch taken from the two rotations in the intact core lysimeter test. The CV was 8% for the cylinders and 4% for the buckets. In both devices, the net gain in weight over the measurement period was equivalent to 8 mm of water. To give a sense of the sensitivity of the lysimeter methods, other unrelated treatments measured at the same time had statistically significant differences of 0.10 mm among five residue levels from 150 and 600 g m^{-2} (Wuest, 2017). The greater levels of residue were considered unrealistic for the Lind location and

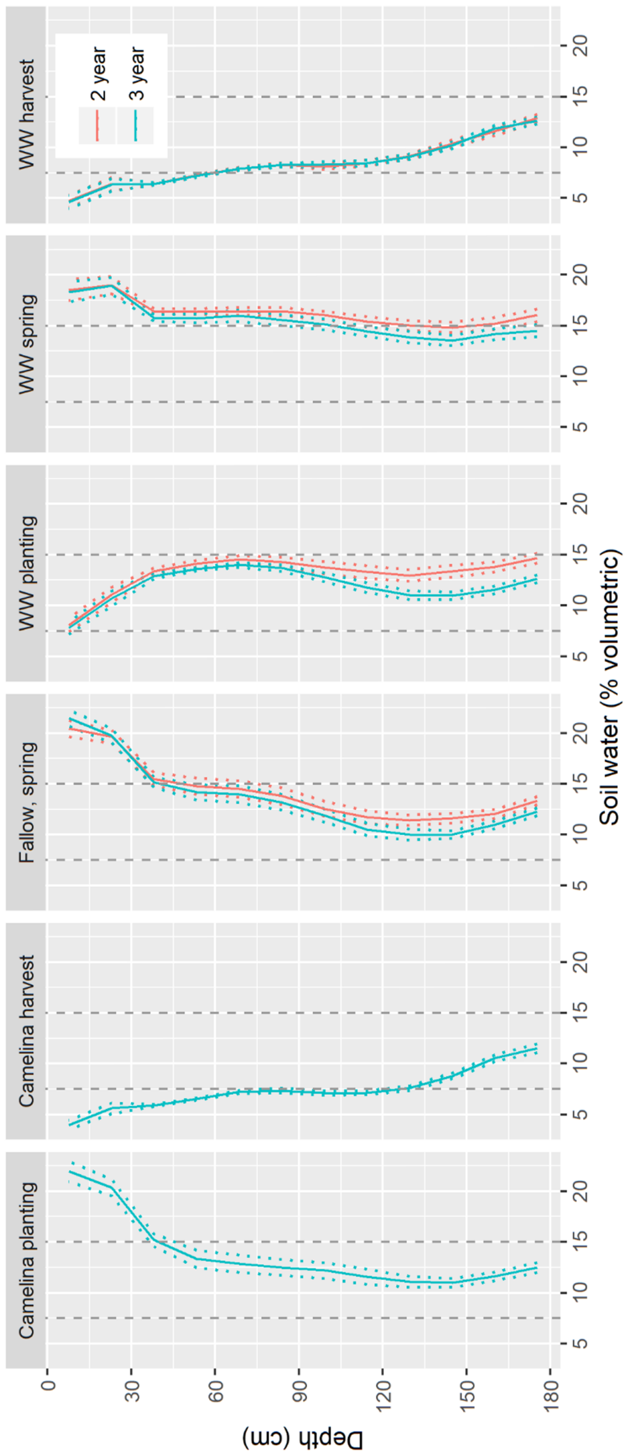

Fig. 2. Six-year average soil water profiles in late spring and late summer comparing a 3-yr camelina–summer fallow (SF)–winter wheat (WW) rotation with a 2-yr WW–SF rotation. Dotted lines show ±1 SE of the mean. Vertical guidelines are placed at 7.5 and 15% volumetric water content for easier comparison. Surface soil (0–45 cm) water differences were small and not statistically significant. The differences began below 45 cm but were greatest deep in the profile at 120 to 180 cm and amounted to an average difference of 21 mm of water within the entire 0- to 180-cm rooting zone at the time of winter wheat planting (Table 1).

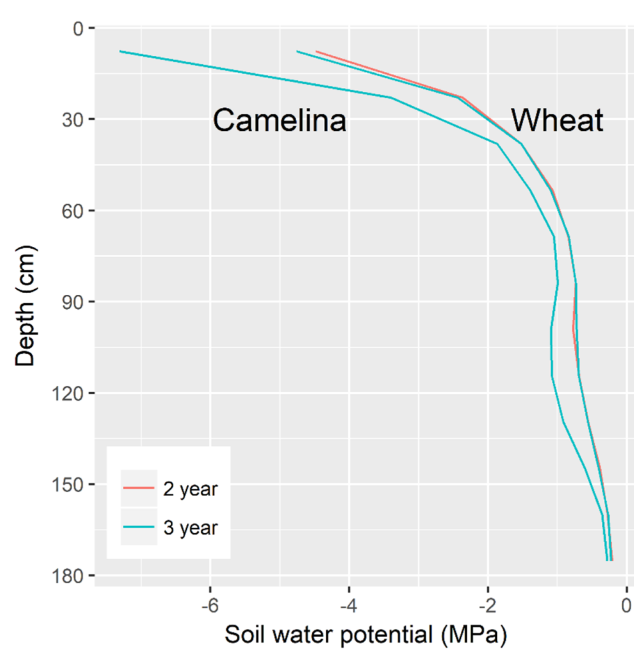

Fig. 3. Harvest water potential profiles following winter wheat in the 2- and 3-yr rotations and camelina in the 3-yr rotation. Data are averaged over 6 yr.

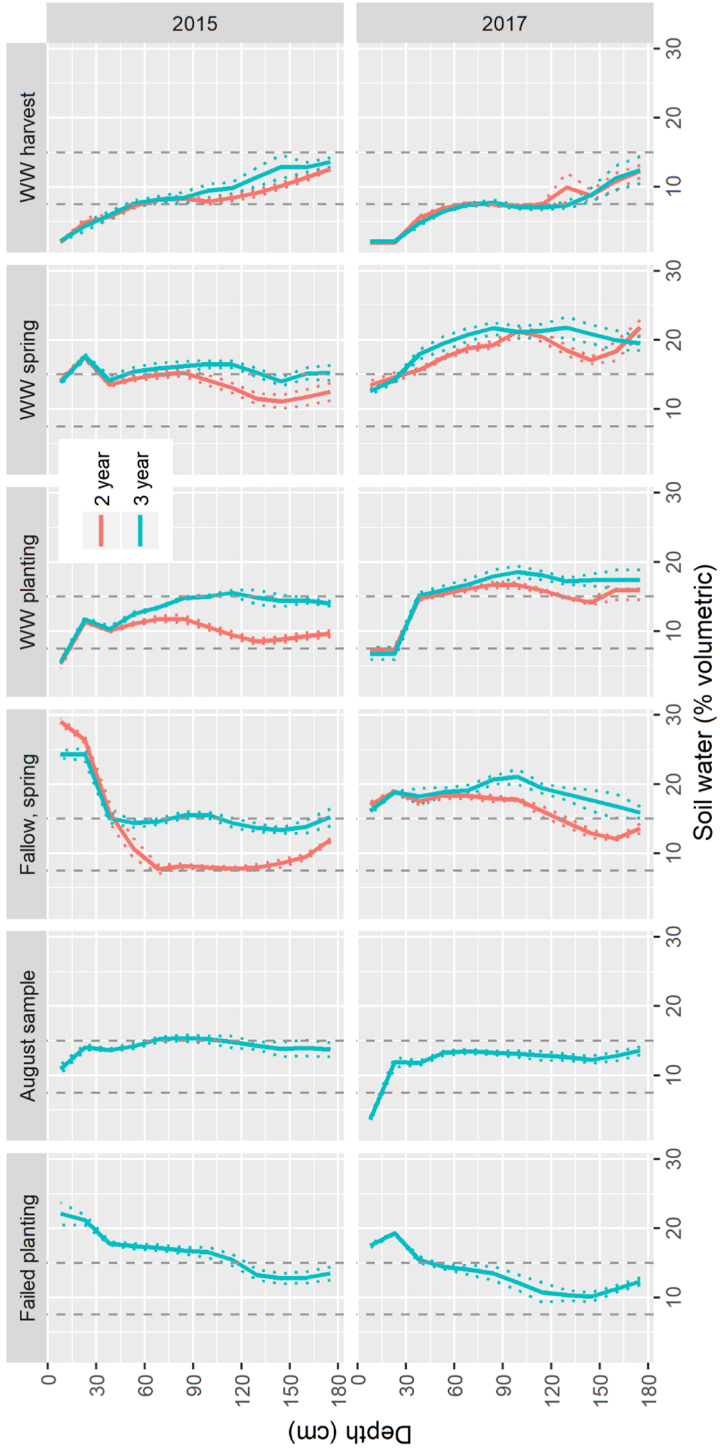

Fig. 4. Soil water profiles in years when the newly emerged camelina seedlings were killed by frost in dry surface soil in early spring. The plots were thereafter left as a weed-free fallow, creating 2 yr of fallow before planting winter wheat. The rotations ended in the years 2015 and 2017 and are compared with the 2-yr winter wheat–summer fallow of the same period.

therefore 150 and 300 g m^{-2} were chosen. Our test compared the two residue types at the same amounts by mass, but spring crops like camelina always produce less residue than WW.

Tillage mulch depth of SF measured on 31 July 2015 averaged 17.6 ± 4.6 cm after WW and 16.7 ± 4.7 cm after camelina. These were not significantly different. An exploratory test of dry aggregate sizes from one plot of each treatment showed no difference in aggregates of any size class. In this very weakly aggregated soil, following one pass of an undercutter sweep, 86% of the soil passed through a 125-µm sieve and only 2% was retained on 500-µm and larger screens. Soil clods (aggregates larger than 1 cm) were a minor proportion of the total soil mulch and were not noticeably different between rotations.

Differences in susceptibility to wind erosion following WW planting were measured by Sharratt and Schillinger (2016), who reported increased erodibility by a factor of 2.5 following camelina compared with WW–SF because there was less surface residue. Residue cover by the line–point method just after planting of WW in the 2-yr rotation averaged 30%; in the 3-yr rotation, it measured 18% (Schillinger, 2019).

Double Fallow

In 2013 and 2015, camelina crop establishment failed. Since the plots were kept weed-free the rest of the spring and summer, this created 2 yr of fallow before seeding WW in these plots. Figure 4 shows the effects of this double fallow on soil water profiles compared with the single-year fallow. Extra water storage resulting from the double fallow was evident in both the drier 2013–2015 cycle and the high-precipitation 2015–2017 cycle. In the spring of 2017, soil below 45 cm had approximately 21% volumetric water content compared with the typical 15% in the spring after planting WW after the fallow (Fig. 2 and Fig. 4).

We calculated marginal (additional yield that could be attributed to additional water) WUE by taking the WW grain yield differences between the two rotations and dividing these by the soil water differences at WW planting (Table 2). The 6-yr average WUE for WW when the treatments were in true rotations was 8.5 kg ha^{-1} mm^{-1}, similar to the dry (2015) double fallow at 9.2 kg ha^{-1} mm^{-1}. The double fallow experiencing higher precipitation (2017) had a marginal WUE of 21.8 kg ha^{-1} mm^{-1}.

DISCUSSION

The soil water profiles revealed that camelina in the 3-yr rotation depleted soil water significantly more than WW in the 2-yr rotation. The deficit persisted through the ensuing fallow year and into spring of the WW crop year. We cannot separate several possible causes that could be responsible for the difference in soil water depletion following the camelina and WW crops. It could be the result of less water being available in the spring following a WW crop compared with the greater water at depth available to WW after fallow. Alternatively, it could be caused by a difference in the species' capacity to extract water to a given water potential or by different rooting patterns. It could also result from different weed spectrums within the crops. Total weed dry biomass averaged 650 kg ha^{-1} in the camelina, 300 kg ha^{-1} in the 3-yr WW, and 275 kg ha^{-1} in the 2-yr WW. Schillinger (2019) suspected that Russian thistle weed pressure in camelina was likely to be a cause of water extraction deep in the soil profile. Whatever the reason(s), growing camelina after WW in the 3-yr rotation consistently reduced stored soil water at the beginning of fallow compared with the 2-yr WW–SF rotation. Although the average difference in WW yields between the 2- and 3-yr rotation was relatively small (170 kg ha^{-1}, Table 2), financial returns on a spring crop that reduces subsequent WW yields need to be substantial to make up for the loss in WW yield and the reduction of WW crop frequency. Lack of residue production leading to potential wind erosion concerns (Sharratt and Schillinger, 2016) and the highly variable yield performance of camelina and other spring crops, (Juergens et al., 2004) are additional considerations.

Table 2. Yield gain attributable to stored water (marginal water use efficiency), including crop-year precipitation totals (1 Sep to 31 Aug).

	Six-year average†	2015	2017
Yield difference (2-yr minus 3-yr), kg ha^{-1}	170	–543	–611
Soil water at planting (total soil profile, 0–180 cm), mm			
2-yr	239	178	319
3-yr	219	237	347
Difference	20	–59	–28
Marginal water efficiency, kg ha^{-1} mm^{-1}	8.5	9.2	21.8
Fallow year precipitation, mm	259	195	322
Winter wheat crop-year precipitation	277	193	375
Total	536	388	697

† The data are the average of 6 yr of winter wheat (WW) harvest comparing the 2-yr WW–summer fallow (SF) rotation with the 3-yr WW–camelina–SF rotation, as well as two additional years where camelina stand establishment failure effectively created 2 yr of fallow before WW planting.

As noted in the Introduction section, a previous long-term study at the same Lind location of SW grown in a 3-yr WW–SW–SF rotation showed that SW consistently used less soil water than WW in a 2-yr WW–SF rotation (Schillinger, 2016) and, unlike camelina, left deep water for subsequent crops. The difference is probably a result of the more effective broadleaf weed control in the spring wheat, where average Russian thisle dry biomass was 105 kg ha^{-1}, (Schillinger, 2016) vs. an average of 325 kg ha^{-1} in camelina (Schillinger, 2019) in this study.

Soil water content after WW harvest was very consistent year to year and between rotations, producing low variance, which demonstrated the ability of WW to extract available water throughout the soil profile consistently and efficiently. Soil water measured in the surface soil, especially the top two 15-cm increments, was mostly influenced by weather and showed little to no effect of rotation. This does not indicate that there were no differences in surface water in certain seasons caused by the difference in rotations. Measurements in the spring, when surface soil is likely to be moist, and again in August, when the weather is typically very dry, are not likely to detect overall trends near the surface, where the weather causes rapid changes and the effects of surface residue are important.

Winter wheat and camelina crop residues differ in quantity, size, and durability, which could affect water infiltration (Wuest, 2017). There were no obvious differences in the soil mulch or other surface soil characteristics except for the quantity and type of residue following camelina compared with after WW. As stated above, residue cover after planting of WW averaged 30% and 18% in the 2-yr versus 3-yr rotations, respectively (Schillinger, 2019).

In the low-precipitation years of 2014 to 2015, the 2-yr rotation gained more water below 60 cm between the March 2014 (fallow, spring) measurement and the August 2014 (WW planting) measurement and again gained more below 60 cm between the August 2014 and April 2015 (WW spring) measurements (Fig. 4). The 3-yr rotation had greater total stored water because of the crop failure soon after planting of camelina, but the gains through the two subsequent winters were much less than with just 1 yr of fallow, demonstrating the inherent inefficiency of a double fallow for soil water storage as well as crop WUE. In addition, the double fallow produced very low residue levels on the soil surface because of soil disturbance caused by two attempts to plant camelina. The low intensity rainfall events during 2014–2015 (Fig. 1) may have been subject to more rapid loss by evaporation in plots with very low amounts of surface residue. Standing WW residue is relatively good at trapping and retaining snow and helps the infiltration of precipitation (Merrill et al., 2007; Wuest, 2017; Wuest and Schillinger, 2011) so perhaps this helped the 2-yr rotation store more water than the 3-yr rotation, in which the WW stubble was mostly gone after the interceding camelina crop.

The high precipitation cycle of 2016–2017, which was coincident with the double fallow in the 3-yr rotation, demonstrates that this soil is capable of long-term storage of much more water than is normally available (Fig. 4). A soil profile that is almost never at field capacity is characteristic of arid and semiarid regions. This is largely caused by water use by plants rather than evaporation.

Greater marginal WUE was realized in a high-precipitation year following a high precipitation SF year. This indicates that relatively small improvements in stored soil water can make substantial yield differences in higher precipitation zones, not just low-precipitation zones. French and Schultz (1984) calculated similar values to ours and similar WUE differences for high-production sites (20 kg ha^{-1} mm^{-1}) and dry sites (5–9 kg ha^{-1} mm^{-1}; <300 mm crop-year precipitation). Lilley and Kirkegaard (2007) measured much greater WUE values in years when roots reached subsoil moisture; their marginal WUE was in the range of 30 to 50 kg ha^{-1} mm^{-1} for all treatments. As in our present study, a higher production year resulted in better marginal WUE. Kirkegaard et al. (2007) measured differences in efficiency related to weather patterns. Under stress before anthesis, WUE was 14 to 21 kg ha^{-1} mm^{-1}. Under stress after anthesis, WUE was 49 to 67 kg ha^{-1} mm^{-1} for deep water use. Again, high values of marginal WUE tended to occur in wetter seasons with high yield potential.

CONCLUSION

Growing spring camelina in a 3-yr WW–camelina–SF rotation resulted in a consistent and highly significant reduction in deep soil water compared with 2-yr WW–SF. This was caused by deep water extraction during camelina growth, which was almost certainly exacerbated by the presence of deep-rooted Russian thistle. This difference in soil water between the two rotation systems continued throughout the ensuring 13-mo fallow period and was probably the cause for the relatively slight but statistically significant reduction in WW grain yield in the 3- vs. 2-yr WW.

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