Camelina: Long-term cropping systems research in a dry Mediterranean climate

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ABSTRACT

Camelina [Camelina sativa (L.) Crantz] is a short-season annual oilseed crop in the Brassicaceae family. Interest in camelina has increased substantially during the past 15 years because the oil is an excellent feedstock for producing low-carbon-emission biofuel and has a unique fatty acid profile as a potential edible oil. Camelina has been promoted as an alternative crop in low-precipitation dryland regions because of its low fertilizer requirement and drought tolerance. An 8-yr field experiment was conducted from 2010 to 2017 at the WSU Dryland Research Station near Lind, WA to compare a 3-yr winter wheat (WW)-spring camelina-summer fallow (SF) rotation with the traditional 2-yr WW-SF rotation. Annual crop-year (Sept. 1-Aug. 31) precipitation ranged from 193 to 375 mm and averaged 281 mm. Camelina seed yield ranged from 339 to 1175 kg/ha and averaged 643 kg/ha. Mean WW yield of 2692 kg/ha in the 3-yr rotation was significantly lower (p = 0.046) compared to 2862 kg/ha in the 2-yr rotation. Soil profile water was significantly lower (p < 0.001) after harvest of camelina compared to after WW harvest in the 2-yr rotation. This soil water reduction was consistently measured throughout the ensuing 13-month fallow cycle. There are no labeled in-crop broadleaf weed herbicides for camelina and populations of Russian thistle (Salsola tragus L.) and tumble mustard (Sisymbrium altissimum L.) were higher in camelina than in WW. This was likely a factor in the deep extraction of soil water in the camelina plots to a depth of 180 cm. Data from this study suggest that, with current cultivars and management practices, camelina is not yet agronomically or economically stable or viable in a 3-yr WW-camelina-SF rotation in the low-precipitation (< 300 mm annual) rainfed cropping region of the Inland Pacific Northwest (PNW).

1. Introduction

Camelina is a dicotyledonous oilseed crop in the Brassicaceae (Cruciferae) family. Though grown in Europe as early as 4000 BC (Larsson, 2013), camelina has only in recent decades received serious attention in the scientific literature. Camelina is a short-season crop that is widely reported in Europe, Canada, and the United States to have a relatively high tolerance to water stress (Hunsaker et al., 2011; Gao et al., 2018; Zanetti et al., 2013) as well as frost tolerance and disease resistance (Zanetti et al., 2017).

Camelina oil can be used as feedstock for biodiesel and jet fuel, food oil, and many other uses as summarized by Berti et al. (2016). After most of the oil is extracted from seeds by mechanical press, the remaining seed meal provides an excellent dietary ingredient to produce animal feed (Moriel et al., 2011). Some farmers both grow and press camelina seed themselves to produce raw oil which can be directly used in oil diesel engines without transmethylation (Keske et al., 2013).

Dependence on imported oil, atmospheric emissions, and other concerns with petroleum-based fuels has led to numerous scientific efforts to seek alternative and renewable energy. Jet fuel derived from camelina oil has undergone extensive testing by commercial airlines and the US military and results show that camelina-based hydrotreated jet fuel meets all jet engine performance expectations and significantly reduces greenhouse gas emissions compared to petroleum-based jet fuel (Shonnard et al., 2010; Corporan et al., 2011; Azami et al., 2017).

A monoculture 2-yr WW-SF rotation is practiced by most farmers on 1.5 million cropland hectares in the low-precipitation (< 300 mm annual) precipitation region of the PNW (Karimi et al., 2018). In recent years, winter pea (Pisum sativum L.) (Schillinger, 2017), winter canola (Brassica napus L.) (Pan et al., 2016), and winter triticale (X Triticosecale Wittmack) have gained popularity among farmers due to their relatively acceptable and stable yield performance; but, like WW, they require a preceding year of fallow to be agronomically and economically viable. Farmers and scientists in this dry region have experimented with many spring-planted cereal and broadleaf crops, but those so far tested are subject to water and heat stresses and have highly-variable yields that...
are not economically stable or attractive in the long term.

Recent agronomy-related research with camelina over three years at four diverse agroclimatic locations in the PNW provided valuable data on the optimum planting date (Schillinger et al., 2012), nitrogen and sulfur fertility requirements (Wysocki et al., 2013), and the best-adapted cultivars (Guy et al., 2014). Results from these experiments provided incentive to establish a long-term camelina cropping systems study near Lind, WA where WW-SF is, by far, the dominant crop rotation and no previous spring-planted crop had been found acceptable (other than on a small scale) by regional farmers.

2. Materials and methods

2.1. Overview

An 8-yr field experiment was conducted from 2010 to 2017 at the Washington State University (WSU) Dryland Research Station near Lind, WA to compare a 3-yr WW-camelina-SF rotation with the traditional 2-yr rotation of WW-SF. Annual crop-year (Sept. 1-Aug. 31) precipitation over the eight years ranged from 193 to 375 mm and averaged 281 mm (Table 1). Long-term (97-yr) average annual precipitation at the site is 244 mm. There were only two years (2014 and 2015) of below-average crop-year precipitation (Table 1). Precipitation averaged 281 mm (Table 1). Long-term (97-yr) average annual precipitation at the site is 244 mm. There were only two years (2014 and 2015) of below-average crop-year precipitation (Table 1). Precipitation was measured at an official US National Weather Service recording site located < 0.5 km from the experiment. In this Mediterranean-like climate, most precipitation occurs during late fall and winter and diminishes from April-June. The months of July-September are mostly dry except for an occasional thunder storm. Pan evaporation from April through September averages 1415 mm. Mean annual temperature at the Lind Station is 9.9 °C. The record high temperature is 45 °C and the record low -32 °C.

The soil is Shano silt loam (coarse-silty, mixed, superactive, mesic, Xeric Haplocambids). These soils are > 180 cm deep with uniform texture throughout with no rocks or restrictive layers other than a thin, weak layer of calcium carbonate accumulation at about 50 cm. Soil textural distribution is 10% clay, 51% silt, and 39% fine sand. Shano is one of the major soil series for dryland wheat farming in east-central Washington. These soils were formed in loess (McDonald et al., 2012).

Experimental design was a randomized complete block with four replications. All phases of both rotations were present every year (total = 20 plots). Individual plots were 9 x 76 m and the total experiment covered 1.39 ha. The entire land parcel used for the experiment was in WW production in 2006. In 2007, spring wheat was grown on plots destined for camelina or SF in 2008. Accordingly, plots going into WW in 2008 were left fallow in 2007. This facilitated the temporal staggering of rotation sequencing so that by 2010 (the first year of data reported here), both rotation sequences had gone through a full cycle as required for proper data reporting for crop-rotation experiments (Cady, 1991).

### Table 1

<table>
<thead>
<tr>
<th>Crop year</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
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<td>42</td>
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<td>2012</td>
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<td>13</td>
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<td>6</td>
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<td>35</td>
<td>64</td>
<td>48</td>
<td>19</td>
<td>10</td>
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<td>13</td>
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</tr>
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</table>

#### 2.2. Field operations, fertilization, planting, and weed control

2.2.1. Summer fallow

A 13-month-long SF period preceded the planting of WW in both the 2-yr and 3-yr rotations. After harvest of camelina and 2-yr-rotation WW, residue from both crops was left standing and undisturbed through mid-to-late April. Glyphosate herbicide was applied in late March at a rate of 0.43 kg acid equivalent (ae)/ha to control weeds. In mid-to-late April, primary spring tillage plus 56 kg/ha aqua NH₃-N + 11 kg/ha thiosulfate fertilizer injection was conducted with an undercutter sweep implement at a depth of 13 cm. The fertilizer required for the subsequent WW crop was applied during undercutting to avoid a separate field operation. The undercutter has wide, narrow-pitch, overlapping, adjustable-pitch blades to slice beneath the soil to disrupt capillary pore continuity which retards evaporation of soil water during the dry summer months (Young and Schillinger, 2012). The undercutter is a conservation-tillage implement because its use retains most of the surface residue and does not pulverize the soil surface (Papendick, 2004). A rodweeder (also a noninversion implement) was used once or twice as needed in late spring and summer at a depth of 10 cm to control weeds. The rodweeder is ground-powered and has a 2-cm square rod that rotates opposite the direction of travel to uproot weeds with little disturbance to surface residue. All SF management and fertilization following camelina and 2-yr-rotation WW were identical and conducted at the same time every year.

2.2.2. Planting

2.2.2.1. Camelina. The camelina cultivar 'Calena' was planted at a rate of 6 kg/ha (McVay and Khan, 2011) in late February or early March. Clean, weed-free seed was obtained every year from a camelina seed producer near Endicott, WA. Calena was selected as it was among the top yielding camelina cultivars and numbered lines tested from multi-location studies conducted by Guy et al. (2014). Glyphosate herbicide was applied at 0.55 kg ae/ha about one week prior to planting. Camelina was direct plowed into the standing stubble of the previous WW crop at a depth < 1.0 cm with a hoe-opener drill with 10 cm paired-row openers spaced 30 cm apart. Solution 32 (ammonium nitrate) provided the base for liquid fertilizer to supply 28 kg/ha nitrogen and 7 kg/ha sulfur (ammonium thiosulfate) that was stream jetted onto plots after camelina emergence and just prior to the arrival of an expected rain event.

2.2.2.2. Winter wheat. Winter wheat in both the 2-yr and 3-yr rotations was planted into carryover soil moisture in SF in late August-early September with a deep-furrow drill with 40 cm row spacing. The WW cultivars used were 'Eltan' for the first five years and 'Otto' in the final three years. Seeding rate was 56 kg/ha and 11 kg/ha granular phosphorus was applied with the seed. Seed was placed an average of 15 cm below the soil surface. Certified WW seed was treated with a fungicide as well as an insecticide for wireworm (Agriotes lineatus) control.
2.2.3. In-crop and post-harvest weed control with herbicides

For camelina, the in-crop post-emergence grass-weed herbicide quinclorac-p-ethyl was applied in April at the maximum labeled rate to control downy brome (Bromus tectorum L.), volunteer WW, and other grass weeds. No in-crop broadleaf weed control herbicides are labeled in the U.S. for use on camelina. For WW, the in-crop broadleaf herbicides used were labeled rates or 2,4-D ester or bromoxynil + MCPA applied in April when wheat plants were between tillering and jointing growth stage.

Broadleaf herbicides were used for control of Russian thistle (Barros et al., 2018) every year following harvest of camelina in early July. Post-harvest herbicides used were 0.90 kg ai/ha glyphosate or 0.42 kg active ingredient (ai)/ha paraquat + 0.21 kg ai/ha diuron. Post-harvest control for Russian thistle in WW was only required in 2014 and 2015 when precipitation was sparse and WW yields were relatively low.

2.3. Surface residue cover after planting winter wheat

Surface residue cover was determined every year after deep-furrow planting of WW in both the 2-yr and 3-yr rotations using the line-transect method as described by Laffin et al. (1981) and Richards et al. (1984) and endorsed by the USDA Natural Resources Conservation Service (NRCS). In brief, a 15-m-long string was stretched perpendicular to planting direction. The string contained 100 beads spaced 15 cm apart. If a bead was over residue, as determine by direct overhead visual observation, it was counted as a “hit”. Five line-transect string counts were conducted in each newly- planted WW plot (total of 8 plots). Newly-emerged WW seedlings were not counted as residue. Data from string counts in each plot were averaged and the percentage of residue was recorded as percent residue cover.

2.4. Soil water

Water content in the soil to a depth of 180 cm was measured three times each year. These times were: (i) in early August after the harvest of camelina and WW (12 plots); (ii) at the end of fallow in late August (8 plots), and; (iii) in late March (all 20 plots). Volumetric soil water content in the 0–30 cm depth was measured from two 15 cm core samples with gravimetric procedures (Dobryj et al., 2012) and then converted to volumetric water content using known soil bulk density values. Volumetric water content in the 30–180 cm depth was determined in 15-cm increments using a neutron probe (Evett et al., 2009).

2.5. Plant stand establishment

Camelina and WW plant stand establishment was determined 20–30 days after planting by counting individual seedlings in one meter of row. These measurements were obtained from three areas in each plot and the numbers then averaged and converted to plants/m².

2.6. Weeds

Just prior to harvest of camelina and WW, the different weed species were identified and collected within a 3 m² sampling frame which was randomly placed in each plot. Each weed species was counted, clipped at ground level, and placed in a separate paper bag. Samples were placed in a greenhouse for at least 30 days until thoroughly air dried and then weighed on a digital scale.

2.7. Yield determination

Yield of camelina and WW was determined in early and late July, respectively, by harvesting a 1.5-m-wide swath through each 76-m-long plot with a plot combine. After harvest with the plot combine, a commercial-size combine was used to harvest the remaining camelina and WW and spread the straw and chaff of these crops.

2.8. Statistical analysis

Analysis of variance (ANOVA) was conducted for soil surface residue cover after deep-furrow planting of WW, plant stand establishment, soil water content, weed species numbers, dry matter accumulation of each weed species, and grain yield using a randomized complete block design ANOVA for each year and a split-plot in time ANOVA across years with treatment as the fixed-effect factor and year as the random-effect factor. Tukey’s honest significant difference (HSD) test was used to detect statistical differences in treatment means and control the experiment-wise error rate for multiple comparisons. All ANOVA tests were done at the 5% level of significance using Statistix 10 data analysis software.

To reiterate, the experiment was established in 2008 but, to allow proper temporal entry for valid comparison of WW in the 2-yr and 3-yr rotations, the first year of “rotation” effect on WW was in 2010 (i.e., camelina in 2008, fallow in 2009, WW in 2010). Therefore, subtracting two rotation establishment years, the field experiment was conducted for eight years (2010–2017). Because camelina plant stand establishment failed in 2013 and 2015 (see Section 3.4), only six years of data were used for ANOVA comparison of WW grain yield. Thus, WW data for 2015 and 2017 were not included in the ANOVA because WW in the 3-yr rotation in 2015 and 2017 had two preceding years of fallow (i.e., “double fallow”).

3. Results

3.1. Soil water use by camelina

At time of planting of camelina in March there was an average of 257 mm water in the 180-cm soil profile (data not shown). Camelina used 121 mm of this stored soil water during its growth and an average of 136 mm of water remained in the soil at the time of camelina harvest (i.e., beginning of the 13-mo fallow in the 3-yr rotation) as shown in (Table 2).

3.2. Soil water during fallow

Soil water content at the beginning of the fallow period (i.e., immediately after harvest of camelina and 2-yr WW) was significantly lower by an average of 21 mm (p < 0.001) in camelina compared to WW (Table 2). Depth distribution of soil water in the 180-cm profile at time of harvest in these two systems was similar in the top 90 cm, but water content was noticeably lower with camelina at the 90–180 cm depth (Fig. 1 green lines).

By late March, the WW stubble held 11 mm more water in the 180-cm profile compared to camelina stubble (Table 2); this meant that the camelina stubble had a 10 mm greater overwinter gain (111 versus 101 mm, p = 0.010, Table 2). This was unexpected because WW produces much higher amounts of surface residue compared to camelina. Generally, the greater the quantity of surface residue, the more water is stored in the soil overwinter (Qiu et al., 2011). However, it has long been known through studies at the Lind location (McCall and Wanser, 1924) and throughout the Inland PNW that the drier the soil, the greater percentage of overwinter precipitation will be stored in the soil. Spatial distribution differences in soil water at each incremental depth in the 180-cm soil profile between WW and camelina stubble in late March (Fig. 1, red lines) remained similar to those measured at the beginning of fallow (Fig. 1, green lines). As an aside, soil water content at time of WW harvest in the 3-yr rotation was 156 mm (compared to 157 mm for WW in the 2-yr rotation (Table 2). Overwinter soil water gain in WW stubble in the 2-yr and 3-yr rotations was identical at 101 mm (3-yr WW data not shown).
Table 2
Soil water content of the 180-cm soil profile at three time periods during the 13-mo fallow period after harvest of winter wheat (WW) in the 2-yr rotation and camelina in the 3-yr rotation. These time periods are: (i) the beginning of fallow, (ii) early spring, and (iii) the end fallow (i.e., just before planting winter wheat in both rotations). Also shown are the overwinter soil water gain and April-to-August soil water evaporative loss, as well as associated precipitation storage efficiency (PSE) during the fallow cycle. Data are averaged over six years and do not include the two years of “double fallow” after failure to achieve camelina stands.

<table>
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<th>Fallow treatment</th>
<th>Timing in fallow period</th>
<th>Soil water (mm)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Beginning (late July)</td>
<td>Spring (late Mar.)</td>
</tr>
<tr>
<td>After 2-yr WW</td>
<td>157</td>
<td>258</td>
</tr>
<tr>
<td>After camelina</td>
<td>136</td>
<td>247</td>
</tr>
<tr>
<td>p-value</td>
<td>&lt; 0.001</td>
<td>0.012</td>
</tr>
</tbody>
</table>

†† PSE (Precipitation Storage Efficiency) is % of precipitation stored in the soil during the 13-month fallow.

Fig. 1. Depth distribution of soil water to a depth of 180 cm measured at three times during the 13-month fallow after the harvest of camelina and 2-year winter wheat (WW). These times were (i) at the beginning of fallow at harvest in July (green); (ii) late March (red), and; (iii) at the end of fallow in late August (blue). Data are average over six years and do not include the two “double fallow” years (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

3.3. Surface residue cover after deep-furrow planting of winter wheat

Surface residue cover after planting of WW in the 2-yr rotation ranged from 15 to 35% and averaged 30% over the years, thus meeting the requirement of 30% or more surface residue to qualify as “conservation tillage” as defined by the USDA-NRCS. Surface cover in the 3-yr rotation, where the crop preceding the fallow year was camelina, ranged from 10 to 27% and averaged 18%. The differences in surface residue cover between the 2-yr and 3-yr rotations were highly significant (p = 0.008).

Sharratt and Schillinger (2016) conducted wind tunnel assessments for the study immediately after planting WW (when the soil is most vulnerable to wind erosion) in early September 2011 and 2012 and reported that blowing dust emissions were 2.5 times greater in the 3-yr versus 2-yr rotation. Sharratt and Schillinger (2016) further stated that even the low-disturbance undercutter conservation tillage method caused too much soil disturbance after a crop of camelina and recommended that farmers practice no-till SF after an oilseed crop in lieu of tillage to reduce wind erosion hazard or forego SF and instead plant a crop in the spring.

3.4. Plant stand establishment

Satisfactory stands of WW in both the 2-yr and 3-yr rotations were achieved from deep-furrow planting into SF every year of the study. Stands ranged from 162 to 184 seedlings/m² and averaged 171 seedlings/m². There were no statistically-significant differences in WW stands between rotations.

Camelina seedlings uniformly emerged from all planting dates with stands ranging from 366 to 480 seedlings/m² and averaging 421 seedlings/m². However, newly-emerged camelina seedlings were killed in two back-to-back planting attempts in 2013 and one planting attempt in 2015 when nighttime cold air temperatures reached -5.6, -5.0, and -2.2 °C, respectively. It is unlikely that these freezing air temperatures were solely responsible as mortality of newly-emerged camelina seedlings from such temperatures has not been previously reported. The near soil surface was relatively dry at time of seeding in both 2013 and 2015 and combined March and/or April rain was substantially below the long-term mean (Table 1). Thus, we suspect that newly-emerged camelina seedling mortality was likely due to a combination of cold temperature and dry surface soil. Two farmers within a 20 km radius of the Lind Station also had complete loss of their camelina stands in 2015, presumably due to these two factors. Therefore, no camelina was produced in the experiment in 2013 and 2015.

3.5. Weeds

3.5.1. Winter wheat

On average, both downy brome population and dry biomass production were more than double in 2-yr versus 3-yr WW (Table 3). These data highlight the benefit of including a spring-planted crop, especially a broadleaf crop, for grass weed control in a typical WW-SF system. Russian thistle, tumble mustard, and tansy mustard (Descurainia pinnata Walt.) populations and their dry biomass production trended higher in 3-yr WW but were not significantly different than in 2-yr WW (Table 3).

3.5.2. Camelina

Good in-crop control of downy brome was achieved in camelina. The grass-weed herbicide quizalofop-p-ethyl was effective, with only one downy brome plant/m² averaged over the six years (Table 3). These populations would be considered extremely low for the WW-SF rotation (Young and Thorne, 2004).

Tumble mustard is a winter annual and the late-winter glyphosate burndown application appeared to completely control this weed every year. However, we suspect some tumble mustard emerged after the...
herbicide application as both population and dry biomass of this weed in camelina were at least five times greater than in 3-yr WW and 18 times greater than in 2-yr WW (Table 3). Mature tumble mustard has a broad canopy structure which can be bothersome to farmers during harvest as this weed easily lodges in the rotating bats of combine headers.

Tansy mustard is also a winter annual weed that, like tumble mustard, appeared to exhibit some plant emergence in the spring following the burn-down glyphosate application. Tansy mustard produced only about 30% of the dry biomass of tumble mustard (Table 3) and was considered less problematic than the later.

Russian thistle was present in camelina in all years (Fig. 2a and b, Table 3). Russian thistle can emerge anytime during the spring after rain showers of 3 mm or more. Camelina plants did not begin rapid aboveground biomass accumulation until late April or early May and, in drier years, did not provide full ground cover at any time during its lifecycle (Fig. 2a). Even in the wetter years when full ground cover was achieved (Fig. 2b), Russian thistle was present under the camelina canopy and required control with herbicides after camelina harvest.

3.6. Yields

3.6.1. Camelina

Clean camelina seed yield ranged from 339 to 1175 kg/ha and averaged 643 kg/ha over the six years (Fig. 3). There was little to no pod shatter in any year. Seed yield increases were generally positively correlated with crop-year precipitation; the lowest (2014) and highest (2016) seed yields were recorded with 195 and 322 mm of crop-year precipitation, respectively (Table 1). Camelina seed yields were low in 2010 despite both crop-year precipitation and May and June precipitation being well above average (Table 1). Above-average precipitation in May and June is well known to greatly enhance yield potential of spring-planted crops in the PNW (Schillinger et al., 2008). We speculate that yield potential was reduced in 2010 due to subfreezing temperatures for six successive nights from May 4–9 with the lowest temperature of −5 °C occurring on May 5. Camelina was in early flowering stage of development during this period.

The average yield of 643 kg/ha is considered low compared to yields of spring canola generally achieved by regional farmers. This observation agrees with findings from a 10-yr study in 14 locations in the rainfed wheatbelt of western Australia where canola produced an average of 42% greater seed yield compared to camelina (Campbell et al., 2013).

3.6.2. Winter wheat

Winter wheat grain yield in the 2-yr WW-SF and 3-yr (WW-C-SF) rotations for eight years. The numbers over the WW yield bars show camelina yield in kg/ha. Within-year and 6-yr-average WW yields followed by a different letter are significantly different at p < 0.05. There were never significant within-year differences in WW yield in the two rotations when a camelina crop was grown in the previous cycle. When stand establishment of camelina failed in 2013 and 2015, WW yields were significantly increased in the 3-yr rotation in 2015 and 2017, respectively, because they had two years of fallow (“double fallow”). The average yield shown is for six years and does not include the two years when WW was grown on double fallow.

Fig. 2. The lowest camelina yield of 339 kg/ha occurred in 2014 (left) when only 195 mm of precipitation occurred during the crop year. Note the infestation of Russian thistle. The highest camelina yield of 1175 kg/ha (right) was in 2016 when 322 mm of precipitation fell during the crop year.
SF rotations averaged 2862 and 2692 kg/ha, respectively, over the six years (Fig. 3). There were never any statistically-significant within-year differences in WW grain yield between rotations, but the 6-yr average grain yield difference was significant at \( p = 0.046 \). Coefficient of variation values for WW grain yield were always considered low and averaged 9.8%. Winter wheat grain yields in 2010 were greater than the 6-yr mean, likely due to abundant May rain and higher than average crop-year precipitation. The six consecutive nights of subfreezing temperatures from May 4–9 were likely not so damaging for WW compared to camelina (see Section 3.6.1 above) because WW was still in the stem elongation phase of development.

4. Discussion

4.1. Soil water

4.1.1. Water use by camelina

The literature suggests that camelina is a “moderate” user of soil water as summarized by Berti et al. (2016), Gesch and Johnson (2015) described camelina as a low water user with 80% of its root mass in the surface 30 cm. George et al. (2018) reported that water use by camelina occurred mostly in the top 100 cm of soil, with some depletion occurring to depths of 150 cm. However, in the current study, water extraction by camelina occurred to 180 cm (Fig. 1). We suspect that the greater use of water below 90 cm by camelina vs. WW was due to Russian thistle. There are no labeled broadleaf herbicides for in-crop control in camelina and Russian thistle was present all years. Russian thistle rapidly extends it taproot deep into the soil even when above-ground growth is modest (Pan et al., 2001). Russian thistle plants achieved a height of no more than 30 cm in the camelina and a fast-acting contact burndown herbicide was used immediately after camelina harvest. We strongly suspect that Russian thistle was largely responsible for water extraction at the lower depths as previously documented by Schillinger and Young (2000).

4.1.2. Overwinter soil water recharge

Over-winter precipitation storage of water in the soil after harvest of camelina was significantly greater than that after harvest of WW. This was unexpected as camelina produced very little surface residue in comparison to WW. It is well known that high quantities of surface residue enhance precipitation storage in the soil during cool, wet winter months (Greb et al., 1970; Wuest, 2018; and others). Possible explanations for the overwinter water storage in this study are: (i) the tap root of camelina may have provided a preferential pathway for water infiltration compared to the fibrous root system of wheat, and; (ii) generally, the drier the soil at harvest, the greater percentage of overwinter precipitation is stored in the soil (Kok et al., 2009).

4.1.3. Spring through summer soil water loss during fallow

Why was significantly more soil water lost to evaporation over the summer in the 3-yr rotation? As shown in Fig. 1, most of change in depth distribution of soil water between the two fallow systems from spring (red lines) to late August (blue lines) occurred below 90 cm. The primary tillage undercutter operation in late April, as well as the one or two subsequent rodweeding operations, were always conducted at the same time and depth in both rotations. There were no noticeable differences in soil clod size within the surface tillage-mulch layer. The main difference was significantly more surface residue present in the 2-yr versus 3-yr rotation. Surface residue, although critical for wind erosion control, has been documented to have only minor influence on fallow soil water retention in the dry PNW summer months (Wuest, 2010, 2018; and others) during what is considered the third stage of soil drying (Idso et al., 1974). Thus, soil water data from this study merit further analysis to help decipher possible reasons for the significant over-summer evaporation rate differences between treatments.

4.2. Camelina cold hardness

Newly-emerged camelina seedlings in the young cotyledon stage of development were killed on three occasions, presumably due to nighttime temperatures that ranged from -5.6 to -2.2 °C combined with dry surface-soil conditions. In a prior field experiment conducted at the same Lind location, Schillinger et al. (2012) reported that camelina (cv. Calena) planted in mid-October withstood −23 °C air temperature for eight hours with no snow cover with sustained winds of more than 30 km/h in December. Camelina seedlings were in the two-leaf stage of development and had, apparently, been hardened adequately from October to December to tolerate this severe cold.

4.3. Differences in winter wheat grain yield between rotations

The grain yield differences between 2-yr and 3-yr WW were subtle, but statistically significant at \( p = 0.047 \) when averaged over the six years (Fig. 3). The average of 170 kg/ha greater yield in 2-yr WW was likely due to the additional 20 mm of water present in the soil at time of planting compared to 3-yr WW (Table 2) as it is in close agreement to that described by Schillinger et al. (2008) for predicting grain yield of WW based on stored summer fallow water in the PNW.

Winter wheat in the 3-yr rotation in 2015 and 2017 had two preceding years of summer fallow (i.e., double fallow) because of failed stands of camelina in 2013 and 2015, respectively (Fig. 3). At time of planting WW in these two double-fallow years, there was an additional 59 and 14 mm of soil water in the 3-yr versus 2-yr rotation; this additional soil water contributed to higher WW yield in the 3-yr rotation in 2015 and 2017. As previously mentioned, the WW yield data for these two years were not included in the mean statistical analysis as they were not in proper rotation sequence for correct comparison of wheat yield the WW-camelina-SF versus WW-SF rotation. As an aside, the practice of double fallow is considered hugely inefficient and is only practiced by farmers during periods of extreme drought.

4.4. A camelina line resistant to soil residual ALS inhibitor herbicides

Acetolactate synthesis (ALS) inhibitor “Group 2” herbicides are commonly used by many farmers for in-crop control of both grass and broadleaf weeds. In low-precipitation environments, these herbicides have soil residual activity for several years. Resistance or tolerance to these herbicides through mutation breeding techniques (Walsh et al., 2012) have been developed for numerous crops, including wheat and canola. No camelina cultivars have had resistance to these residual herbicides and, this alone, has discouraged many farmers from considering camelina in their crop rotation. The camelina numbered line ‘WA-HT1’, which is resistant to soil residual levels of Group 2 herbicides, was recently registered by WSU (Hulbert et al., 2018). The expected release of WA-HT1 will create the opportunity for farmers to grow camelina on cropland where it previously was not possible.

4.5. What about winter camelina?

There has been recent interest in winter camelina for the US northern Midwest region as a cover crop, double crop, or relay crop with soybean (glycine max L.) in the 2-yr maize (Zea mays L.)-soybean rotation that is widely practiced throughout this region (Berti et al., 2017; Gesch et al., 2018). These camelina cultivars are true winter types as they require a cold period for vernalization. Fall-planted Calena did not fare as well as late-winter planting at four diverse locations in the PNW because fall-emerging broadleaf weeds were problematic (Schillinger et al., 2012). Winter camelina has a different development pattern as well as its own base temperature to grow, thus could be more competitive than the spring-type Calena against broadleaf weeds emerging in the fall. Winter camelina cultivars have not been well tested in the PNW. Winter camelina cultivars tend to be lower yielding
than spring-planted cultivars in the US Northern Midwest (R.W. Gesch, personal communication).

4.6. Interest in camelina by Pacific Northwest farmers

To date, PNW farmers have shown little interest in producing camelina. The USDA-Farm Service Agency offered a program entitled the Biomass Crop Assistance Program (BCAP) in 2011 to provide farmers incentive to grow camelina to produce biofuel feedstock to reduce U.S. dependence on fossil fuels. The average incentive offered to BCAP to grow camelina in Washington’s dry WW-SF region was $158 per hectare/year over a 5-year contract period (Young et al., 2012). Not a single farmer applied for the program.

5. Conclusion

Interest in camelina throughout the world has soared in recent years due to its low input requirements, good tolerance of abiotic stresses, unique edible oil and seed meal products, and as feedstock for biofuels and other products. Average camelina yield in our experiment was 643 kg/ha, which regional farmers did not consider either agronomically or economically attractive. Growing camelina in a wheat-based rotation did not enhance the subsequent WW yield compared to the 2-yr WW-SF rotation. Although the ability to effectively control grass weeds in camelina is a big benefit, the lack of in-crop broadleaf herbicides as well as lack of federal crop insurance are deterrents. Interest in growing camelina would likely improve as new cultivars, agronomic and management practices, and government programs are developed and refined. For example, during the past 10 years, winter canola production in the PNW dryland region has rapidly expanded (Sowers et al., 2012) due to a focused multidisciplinary research and extension effort by university, USDA, and private-company scientists (WOCS, 2018), the development of cultivars with herbicide tolerance/resistance and other attributes, and the availability of federally-subsidized crop insurance.

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