Received: 2 March 2020 | Accepted: 1 July 2020 | Published online: 3 September 2020

DOI: 10.1002/agj2.20354

Agronomy Journal

WATER, SOIL, CROPS, AND PEOPLE IN A CHANGING CLIMATE: THE AGRONOMIC LEGACY OF DR. B.A. STEWART

New winter crops and rotations for the Pacific Northwest low-precipitation drylands

William F. Schillinger

Department of Crop and Soil Sciences, Washington State University, Dryland Research Station, 781 E. Experiment Station Road, Lind, WA 99341, USA

Correspondence
Department of Crop and Soil Sciences, Washington State University, Dryland Research Station, 781 E. Experiment Station Road, Lind, WA 99341, USA.
Emai: william.schillinger@wsu.edu

Funding information
Washington Oilseeds Cropping Systems (WOCS) project, Grant/Award Number: 1017286; USDA National Institute of Food and Agriculture, Grant/Award Number: 1017286

Abstract
This article is an overview of recent advances in dryland cropping in the region of the Inland Pacific Northwest of the United States (PNW) that receives <300 mm annual precipitation. The climate of the region is Mediterranean-like with wet winters and dry summers. For the past 130 yr, monocrop 2-yr winter wheat (*Triticum aestivum* L.)–fallow (WW–F) has been the dominant rotation practiced on >90% of rainfed cropland throughout this region. Rapid advances in technology in the past several decades and the realities of dryland farm economics prompted most farmers to expand their land area and adopt conservation tillage and no-tillage practices. Three relatively new crops have gained some foothold in the past decade. These crops are winter pea (WP) (*Pisum sativum* L.), winter canola (WC) (*Brassica napus* L.), and winter triticale (WT) (*X Triticosecale Wittmack*). Like WW, all three of these "new" winter crops need to be planted in late August–early September into carryover soil moisture after a 13- to 14-mo fallow period to achieve optimum yield potential. Researchers and farmers have experimented with a multitude of spring-planted crops but, to date, all have shown high year-to-year variability in yield and none have been economically viable in the long term. The focus of this paper is to summarize major research conducted on WP, WC, and WT, as well as farmers' attitudes on the potential of these three winter crops for wheat-based rotations in the PNW drylands.

1 | INTRODUCTION

1.1 | Overview of the region

The rainfed cropping region of Inland Pacific Northwest of the United States (PNW) is divided into three average annual precipitation zones: (a) low, <300 mm of precipitation; (b) intermediate, 300–450 mm of precipitation; and (c) high, 450–600 mm of precipitation. Rainfed (i.e., dryland) crops are grown on approximately 3,350,000 hectares of which 1,557,000 ha is in the low-precipitation zone (Schillinger & Papendick, 2008). The focus of this paper is the low-precipitation zone (Figure 1).

The PNW climate is Mediterranean-like, with about 70% of annual precipitation falling from October through March and 25% from April through June. July through September is the driest period. Precipitation mostly occurs with frontal weather systems from the Pacific Ocean with prevailing westerly winds. Precipitation intensities and volumes are low, usually not exceeding 2–3 mm h^{-1} and

Abbreviations: PNW, Inland Pacific Northwest of the United States; SW, spring wheat; WC, winter canola; WP, winter pea; WT, winter triticale; WW, winter wheat.

10–20 mm per event. Infiltration rates average 15 mm h^{-1} on unfrozen soils (Zuzel & Pikul, 1987).

Winter temperatures are cool to cold and can drop to −24 °C with occasional artic cold winds moving South from Canada. High-pressure systems during the summer lead to warm-to-hot, dry conditions and low relative humidity. Average afternoon temperatures in summer range from 25 to 35 °C.

Soils are primarily silts and fine sands. dominated by particulates <100 microns in diameter, and are vulnerable to wind erosion by direct suspension (Sharratt, Feng, & Wendling, 2007). Soils in the driest southwestern peripheries have the highest sand and lowest organic matter contents and soils gradually increase in silt, clay, and organic matter in a northeasterly direction with increasing precipitation. Most soils are derived from loess deposits and are generally uniform in texture throughout the profile to underlying basalt bedrock (Busacca, 1991). Soil depth for dryland cropping ranges from <90 to well more than 180 cm.

The biggest concern for soil quality in the PNW drylands is fine-particulate dust emissions that occurs in dust storms from dry and unprotected surface soil (Sharratt et al., 2007). Soil organic C has decreased substantially since the onset of farming in the 1880s (Machado, Rhinhart, & Petrie, 2006), with most of this C loss attributed to emission and off-site transport of airborne dust particulates during high-wind events (Sharratt, Kennedy, Hansen, & Schillinger, 2018). Best management practices to control wind erosion in the PNW drylands have been provided by Papendick (2004), Schillinger and Papendick (2008), and several others. Potential future shifts in cropping systems in the region in response to climate warming are outlined by Karimi, Stöckle, Higgins, Nelson, and Huggins (2017) and Stöckle et al. (2018).

1.2 | Winter wheat–fallow dominates

A 2-yr winter wheat–fallow (WW–F) (only one crop every 2 yr) is, by far, the most common crop rotation practiced by farmers in the low-precipitation zone for the past 130 yr (Figure 2). The driest portion of the low-precipitation wheat (*Triticum aestivum* L.) region is the Horse Heaven Hills of south-central Washington that receives as little as 150 mm average annual precipitation (Figure 1). This is considered the driest for rainfed wheat production in the world. Average WW yields after fallow range from 1,350 to 4,400 kg ha^{-1} with 150 and 300 mm of annual precipitation, respectively. Experience to date shows that WW in the drylands requires a preceding 13-mo fallow period to allow sowing into stored soil moisture in late August–early September to produce an economically viable yield. Wheat grain yields have continued to increase in a near linear manner by an average of 28 kg ha^{-1} yr^{-1} (Schillinger & Papendick, 2008) since reliable county-wide grain yield data became available in the late 1920s. These ongoing gains in WW grain yields are due to advances in breeding and genetics, farm equipment, agronomic practices, and other factors (Figures 3 and 4).

Core Ideas

- Winter wheat–fallow is the dominant cropping system in the PNW drylands.
- Yields of spring-planted crops are highly variable and generally not profitable.
- Winter pea, winter canola, and winter triticale are stable with high yield potential.
- Farmers are enthusiastic and increasing land area planted to these new winter crops.

1.3 | Spring-planted crops not suitable

As an alternative to the 2-yr WW–F rotation, farmers and scientists have experimented with a wide array of spring-planted cereal and broadleaf crops such as wheat, barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), pea (*Pisum sativum* L.), canola (*Brassica napus* L.), camelina [*Camelina sativa* (L.) Crantz], condiment mustard (*Brassica* spp.), chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* L.), safflower (*Carthamus tinctorius* L.), sunflower (*Helianthus annuus* L.), and flax (*Linum usitatissimum* L.) (Figure 5). Spring-planted crops so far tested are subject to water and heat stresses due to their later flowering and grain fill and have highly variable yields that are not economically stable or attractive in the long term. Only 3% of farmland in the PNW dryland zone is planted to spring wheat (Huggins, Pan, Schillinger, Young, & Machado, 2015); and land area planted to other spring crops in the drylands is miniscule. Economic studies (Juergens, Young, Schillinger, & Hinman, 2004; Young, Alldredge, Pan, & Hennings, 2015) have shown that spring wheat and other spring-planted crops, by a wide margin, are not economically competitive with early-sown WW in the drylands of east-central Washington. Winter wheat is expected to have even further yield advantages over spring wheat and other spring-planted crops with warmer summer temperatures predicted for the dryland PNW in climate prediction models (Karimi et al., 2017; Stöckle et al., 2018).

As an aside, although not profitable or competitive in the low-precipitation zone, several of the aforementioned spring-planted crops do relatively well in the PNW intermediate- and high-precipitation zones and are

FIGURE 1 The low (<300 mm annual) precipitation zone of east-central Washington and north-central Oregon covers 1.56 million cropland hectares. The 2-yr winter wheat–fallow rotation is the dominant cropping system practiced by farmers throughout this zone

FIGURE 2 The topography of the low precipitation cropping zone is gently rolling. Most farmers have about half their land planted to winter wheat and the other half in fallow, although many farmers also have some land enrolled in the federal Conservation Reserve Program. Land area planted to winter pea and winter canola, and to a lesser extent winter triticale, has increased substantially in the past 10 yr. (Photo credit: W. F. Schillinger)

integral to the 3-yr WW–spring crop–F (intermediate zone) and annual cropping WW–spring crop–spring crop (high zone) rotation systems. Detailed descriptions of current as well as potential future rainfed cropping systems and scenarios in all three PNW precipitation zones are found in Schillinger, Papendick, Guy, Rasmussen, and van Kessel (2006) and Kirby, Pan, Huggins, Painter, and Bista (2017).

1.4 | Interest and need for new winter crops

In the past 15 yr, farmers in the low-precipitation zone have begun planting some land area to winter pea (WP), winter canola (WC), and winter triticale (WT). Like WW, these three new winter crops need to be planted in the late summer after a year of fallow to achieve optimum yield (Figure 4). The objective of this paper is to briefly describe the experiences to date of farmers and scientists with WP, WC, and WT and the potential these crops may have in the future.

FIGURE 3 Buildings and grounds of the Washington State University Dryland Research Station near Lind, WA. The Lind Station was founded in 1915 to "promote the betterment of dryland farming" in the low-precipitation zone. The Lind Station covers 525 ha with 130 ha currently available for field experiments. Average annual precipitation at the Lind Station is 244 mm; the lowest for any federal or state rainfed agricultural research station in the United States. (Photo credit: Tim Smith)

FIGURE 4 This plot drill is representative of deep-furrow split-packer drills used by Inland Pacific Northwest dryland farmers in late August–early September to plant wheat, pea, canola, and triticale into carryover seed-zone moisture after a 13-mo fallow period. All four of these winter crops need to be planted during this brief time window to achieve optimum yield potential. Seed (except for canola) is placed as deep as 18 cm below the soil surface to reach adequate moisture. This 2.5-m-wide plot drill has rows spaced 43 cm apart to allow for creation of deep furrows to minimize depth of soil covering the seed. The drill was fabricated by Washington State University agricultural research technician John Jacobsen at the Lind Dryland Research Station. (Photo credit: W. F. Schillinger)

FIGURE 5 A long-term multifaceted rainfed cropping systems experiment was established on the Ron Jirava farm near Ritzville, WA, in 1997. The experiment covers 8 ha with 56 individual 150-m-long plots. Long-term Average annual precipitation at this Ritzville site is 292 mm. (Photo credit: W. F. Schillinger)

2 | WINTER PEA

Inserting a legume crop into wheat-based rotations has rotational benefit on the subsequent wheat which has been well documented in numerous studies around the world (Arshad, Soon, & Azooz, 2002; Krupinsky, Tanaka, Merrill, Liebig, & Hanson, 2006; Miller, Gan, McConkey, & McDonald, 2003; Williams et al., 2014).

Dry pea is a pulse crop. Pulse crops are cool-season annual grain legumes that have edible seeds. With symbiotic bacteria, pulses fix atmospheric N adequate for their needs. Dry pea is primarily grown in North Dakota, Montana, and the Canadian provinces of Saskatchewan, Alberta, and Manitoba, with a combined 2019 harvested area of 1.79 million ha in these regions (Agriculture and Agri-Food Canada, 2019; USDA-NASS, 2019a). Due to cold winter air temperatures, essentially all dry pea produced in these northern Great Plains regions is spring planted. Spring dry pea is harvested on approximately 40,000 hectares each year in the high-precipitation (>450 mm average annual) Palouse region of Washington and Idaho (USDA-NASS, 2019a). Spring dry pea (and other spring-planted pulse crops) are an important component of diversified and profitable wheat-based rainfed cropping systems in these regions (Chen et al., 2006; Miller et al., 2003; Miller et al., 2015).

Essentially no spring pea is grown in the PNW drylands (i.e., <300 mm annual precipitation) because water and heat stresses commonly occur during flowering and pod fill. Such abiotic stresses limit yield potential of spring pea whereas WP better avoids such abiotic stresses by reaching physiological maturity before the onset of high

FIGURE 6 Winter pea (WP) planted deep into chem fallow near Ritzville, WA. Adequate soil seed-zone moisture for germination and seedling emergence of crops in chem fallow is often located deeper in the profile than in tilled fallow; however, this is not a problem for WP as they have excellent seedling emergence from deep planting depth. (Photo credit: W. F. Schillinger)

air temperatures. Food quality WP was harvested on approximately 5,000 hectares in the PNW drylands in 2019 (Howard Nelson, personal communication, 2019).

2.1 | Why winter pea?

Food quality WP (not to be confused with Austrian winter pea [*Pisum sativum* subsp. *arvense*]) was introduced to the PNW about 20 yr ago. Early research by Chen et al. (2006) showed fall-planted WP yielded as much as 1,830 kg ha^{-1} more than spring-planted pea cultivars. Some farmers in the PNW drylands began to assess WP on their farms in 2006.

Winter pea has a large seed size relative to wheat and can easily emerge from deep planting depths in fallowed soils with 15 cm or more soil cover (Figures 6 and 7), even after the formation of heavy soil crusts when rain showers occur after planting and before emergence. New WP cultivars can tolerate winter temperatures down to –21 °C (Nelson, 2017). Such level of cold tolerance approaches that of PNW winter wheat cultivars. Winter pea can be grown in rotation with Clearfield WW as they tolerate the soil-residual imozamox herbicide [5-(methoxymethyl)-2-(4-methyl-5-oxo-4-propan-2-yl-1*H*-imidazol-2-yl)pyridine-3-carboxylic acid] used in the Clearfield wheat production system. In fact, imozamox herbicide can be applied in-crop to WP for weed control, although many farmers are reluctant to use any soil-residual herbicides as it limits the rotation to non-Clearfield wheat cultivars. The grass weed herbicide quizalofop (quizalofop-p-ethyl) can be used on WP to effectively control downy brome (*Bromus tectorum* L.) and other grass weeds that are a huge problem in monoculture WW–F (Young & Thorne, 2004). Current WP cultivars have an upright growth habit (i.e., they do not lay down or lodge) and can be planted and harvested with drills and combines used for wheat production. Finally, WP is a reliable crop that provides consistently decent yields in both wet and dry crop years (Schillinger, 2017).

FIGURE 7 Winter pea seedling emergence from deep planting depths. Research to date suggests that the deeper the planting depth, the higher the yield potential. Winter pea will emerge without problem even after the formation of hard surface-soil crusts caused by heavy rain that can occur after planting but before emergence. (Photo credit: Stephen Guy)

2.2 | Status of current winter pea cultivar development

Only two food-grade WP cultivars are currently available to farmers in the PNW. The cultivar Windham (McPhee, Chen, Wichman, & Muehlbauer, 2007) is a yellow WP that has a mature plant height of 51 cm, a mottled seed coat, and an average 100-seed weight of 14 g. Windham has recently been replaced by the new WP cultivar Blaze (Pro-Gene Plant Research, Othello, WA). Blaze has a mature plant height of 66 cm, a mottled seed coat, and an average 100-seed weight of 18 g. In addition, Blaze has substantially better cold tolerance than Windham (Nelson, 2017).

The above-mentioned WP cultivars are suitable for the cover crop seed market and the U.S. Government food aid (i.e., PL 480) program to developing countries. In addition, the protein, starch, and fiber components of fractionated flour of both Windham and Blaze is widely used in numerous ingredients for both human and pet foods. However, the term "food grade" is somewhat a misnomer because neither Windham nor Blaze fully meet the criteria for marketing as whole pea or split pea in prepackaged containers or in bulk bins in the United States and other developed countries. Edible whole- and split-pea are expected to have a minimum 100-seed weight of 19 g, a smooth, unpigmented seed coat, and clear hilum.

True edible WP cultivars will likely soon be available to PNW dryland farmers. Rebecca McGee, USDA-ARS pulse crop breeder in Pullman, WA, has four WP numbered lines that have been approved for preliminary release and breeder seed increase (R. McGee, personal communication, 2019). These four lines have 100-seed weights that range from 19 to 22 g, smooth, unpigmented seed coats, and clear hilum. They have excellent cold tolerance and a 5–10% average yield advantage over Windham and Blaze (R. McGee, personal communication, 2019). In addition, three of these new WP lines are green colored. Green-colored dry pea generally fetch a higher price than yellow pea in the whole- and split-pea markets.

2.3 | Long-term winter pea cropping systems research in the drylands

A 9-yr WP cropping systems experiment was conducted from 2010 to 2019 at the Ron Jirava farm near Ritzville, WA (47.16394,–118.473225). The soil at the site is a Ritzville silt loam (coarse-silty, mixed, superactive, mesic Calcidic Haploxerolls). The soil is more than 2-m deep with uniform texture throughout the profile and with no rocks or restrictive layers. Slope is <1%. Long-term (100-yr) annual precipitation at/near the site averages 292 mm. Annual crop-year (1 September–31 August) precipitation over the 9-yr study period ranged from 256 to 440 mm and averaged 328 mm.

2.3.1 | Materials and methods

The objective of the experiment was to compare two 3-yr crop rotations. These rotations were: (a) WP–spring wheat (SW) –F vs. (ii) WW–SW–F. Experimental design was a randomized complete block with four replications. All phases of both rotations were present every year for a total of 24 individual plots. Size of individual plots was 5 by 30 m (Figure 8).

FIGURE 8 Winter pea fixes its own N, allows for control of grass weeds such as downy brome, has good winter hardiness, produces stable yields, and requires no additional machinery other than what is needed to grow wheat. Photo is from the long-term ongoing winter pea cropping systems experiment near Ritzville, WA. (Photo credit: W. F. Schillinger)

A detailed description of all field operations for the experiment are reported in Schillinger (2017) and are summarized here. For the WW–SW–F treatment, fertilizer was applied for WW. No fertilizer was applied to the WP. Winter pea (cultivar Windham from 2010 to 2016 and cultivar Blaze 2017–2018) and WW (cultivar Xerpha from 2010 to 2016 and cultivar Otto from 2017 to 2018) were planted at the same time with 10–12 cm of soil covering the seed each year in the last week of August or first week of September with a deep-furrow drill with 43-cm spacing between rows (Figures 4 and 6). Winter pea seed was inoculated with powdered rhizobium bacteria at the time of planting to facilitate root nodulation and fixation of atmospheric N. Excellent stands of both WP and WW were achieved every year.

Spring wheat (cultivar Louise) was planted and fertilized in late March in one-pass directly into the undisturbed soil and residue left from the previous WP or WW crop. A no-till hoe-opener drill was used to place seed in paired rows 10-cm apart with 30 cm spacing between openers. Fertilizer was placed in a band between and 3 cm below the paired rows. Prior to SW planting and fertilization, soil samples were obtained from 2014 to 2019 in 30-cm increments from the middle of each plot to a depth of 120 cm in all four replicates, then combined to make one sample for each treatment per depth increment, where the previous crop was WP or WW. Soil samples were then analyzed for N, P, K, S, and other nutrients at a commercial soil-testing laboratory. Fertilizer rate for SW was based on soil

TABLE 1 Grain yield of winter pea (WP) and winter wheat (WW), as well as the subsequent yield of spring wheat (SW) following both WP and WW over a 9-yr period at Ritzville, WA

Crop	Grain yield 2011	2012	2013	2014	2015	2016	2017	2018	2019	Avg.
	kg ha^{-1}									
	Winter crop									
Winter pea	2,193	3,158	2,336	–[a]	1,696	2,833	3,058	2,412	2,792	2,560[b]
Winter wheat	5,180	5,719	5,841	3,372	4,211	4,932	5,300	5,486	4,387	4,936
	Spring crop[c]									
SW after WP		2,011	2,992a	1,043	2,293a	3,151	2,210	2,830	1,715	2,281
SW after WW		2,152	2,700b	965	1,704b	3,086	2,274	2,911	2,233	2,253
	Crop-year precipitation[d]									
	mm									
	330	293	319	256	261	370	440	367	319	328

[a] Winter pea winterkilled in 2014 and was replanted to cultivar Banner spring pea, which yielded 870 kg ha^{-1}.
[b] Winter pea average is for 8 yr (i.e., 2014 not included).
[c] ANOVA is for spring wheat only. Within-column means followed by a different letter are significantly different at $P < .05$.
[d] Crop-year precipitation at Ritzville from 1 September –31 August.

test residual soil fertility, available soil water, and perceived grain yield potential. Although soil fertility values following WP vs. WW differed somewhat, SW after either WP or WW always received the same fertilizer application rate each year. Excellent stands of SW were achieved every year.

Crop yields were determined in early to mid-July (WP) and early August (WW and SW) by harvesting a swath through the center of each 30-m-long plot with a plot combine. After grain harvest with the plot combine, the remaining standing crops in the experiment were harvested with a commercial-sized combine for uniform spreading of straw and chaff.

Herbicide weed control methods used in the experiment are reported in Schillinger (2017) and, therefore only briefly mentioned here. Importantly, imazamox soil-residual herbicide was recently labeled for use in WP and, beginning in 2017, 0.15 L ha^{-1} imazamox herbicide was tank mixed with 0.1 kg a.i. ha^{-1} quizalofop grassweed herbicide and applied to WP in the spring. From 2011 to 2016, only bentazon [sodium 3-(1-methylethyl)-1H-2,1,3-benzothiadiazin-4(3H)-one 2,2-dioxide] and MCPA amine (dimethylamine salt of 2-methyl-4-chlorophenoxyacetic acid) were used as they are the only non-soil-residual broadleaf-weed herbicides labeled for use in WP. Full details of herbicide use for broadleaf and grass weeds for WW and SW in this experiment are found in Schillinger (2017).

Soil water was measured to a depth of 180 cm three times each year: (a) in early August immediately after WP, WW, and SW grain harvest (16 plots); (b) at the end of fallow in late August for the fallow plots (eight plots); and (c) in mid-March (all 24 plots). See Schillinger (2017) for further details on these soil water measurements.

2.3.2 | Results and discussion

From 2011 to 2019 yield of WP ranged from 1,696 to 3,158 kg ha^{-1} and averaged 2,560 kg ha^{-1} (Table 1). Winter wheat grain yield over this 9-yr period ranged from 3,372 to 5,841 kg ha^{-1} for an average of 4,936 kg ha^{-1} (Table 1). Spring wheat grain yield was significantly greater following WP vs. following WW in 2013 and 2015 but in other years there were no treatment differences. The 8-yr average SW grain yield of 2281 kg ha^{-1} following WP was not statistically different from the average SW yield of 2253 kg ha^{-1} following WW (Table 1).

Why was SW grain yield after WP not greater than that for SW after WW? Dozens of studies conducted around the world have documented significant yield gains in wheat following dry pea vs. after wheat (Krupinsky et al., 2006; Miller et al., 2003; Williams et al., 2014). For the first 6 yr of this field experiment, Schillinger (2017) reported an additional 30 mm of soil water in the 180-cm profile at time of harvest of WP vs. WW. However, by late March at the time of planting SW this difference was only 13 mm because the tall, thick WW stubble provided a higher overwinter precipitation storage efficiency in the soil compared to sparse WP residue. These comparative soil water dynamics between WP and WW did not change in the later years of the experiment (data not shown).

Spring wheat yields have been numerically, but not significantly, lower following WP vs. WW since we started using the soil-residual herbicide imazamox for weed control in WP in 2016 (Table 1; see Section 2.3.2.). Although the 0.15 L ha^{-1} rate of imazamox used is only half of that recommended for WP for a 4-yr WP–F–WW–F rotation, SW was planted 11 mo after imazamox application, not the 16-mo period from application to WW planted in the WP–F–WW–F rotation. Imazamox-tolerant SW cultivars have just recently been released and these are now used in the experiment beginning in 2020.

2.3.3 | Attitude of dryland farmers about winter pea

Famers like WP because they have unsurpassed emergence from deep planting depths, fix their own N, have stable yield, and provide a means to control grass weeds and soil-borne wheat diseases on fields that have been in monoculture WW–F for many decades. However, the economics of growing WP vs. WW can be a concern. Schillinger (2017) reported that while gross returns of WW exceeded those of WP in most years, when the N fertilizer cost for WW was factored, the adjusted gross returns for WP and WW were similar.

The price farmers receive for WP through the marketing pool provided by Highline Grain Growers, Inc. in Reardan, WA (note: all WP is currently marketed through this pool) during the 2011–2016 crop years reported by Schillinger (2017) averaged US\$364 Mg^{-1}. In the 3 yr following (i.e., 2017–2019) the WP market pool price averaged \$188 Mg^{-1}.

Why such a huge market price decline for WP in recent years? Trade tariffs are a big factor. India imposed a 50% tariff on all imported grain legumes to provide incentive and price support to Indian farmers to grow enough grain legumes to fulfill the huge demand by Indian consumers. Also, the seed of current WP cultivars available to PNW farmers have a mottled seed coat, cloudy hilum, are not quite large enough to enter the true whole-pea and split-pea food markets.

The soon expected release of "true" food quality WP cultivars (see Section 2.2) will almost certainly increase their market value over existing cultivars (Rebecca McGee, personal communication, 2019). In addition, there is ever-increasing interest in the high-protein and gluten-free fractionated flour of WP as an ingredient in numerous foods.

3 | WINTER CANOLA

In the past 15 yr canola has become an increasingly important rotation crop due to mostly favorable economics and interest in regionally produced edible oil and feedstock for biodiesel production (Long et al., 2016; Maaz et al., 2018; Pan, Young, Maaz, & Huggins, 2016). Canola was harvested from almost 29,000 hectares in Washington in 2019 (USDA-NASS, 2019b). The majority was spring canola planted in the intermediate- and high-precipitation zones of the state. Farmers in the low-precipitation region of the PNW (Figure 1) rarely plant spring canola due to drought and/or heat stress during flowering that limits yield potential. Instead, these farmers plant WC after a year of fallow which allows for onset of earlier and extended flowering during more favorable climatic conditions. For this reason, WC has three times the yield potential of spring canola in the low-precipitation zone. Approximately 8,500 hectares of WC was harvested in the low-precipitation zone of the inland PNW in 2019 (Pacific Northwest Canola Association, 2019).

3.1 | Rotation benefits of canola in wheat-based rotations

Like leguminous crops (see Section 2 on winter pea), canola is known to provide several rotation benefits in wheat-based systems (Bushong, Griffith, Peeper, & Eppling, 2012; Harris, Scammell, Miller, & Angus, 2002; Kirkegaard, Christen, Krupinsky, & Layzell, 2008). Canola serves as a break or non-host crop for many important soilborne pathogens (Smith, Kirkegaard, & Howe, 2004) which includes providing a biofumigant effect against soil-borne pathogens because of the breakdown products of glucosinolates (Angus et al., 2015; Smith & Kirkegaard, 2002). As with WP, in-crop grass-weed herbicides can be used with canola to effectively control downy brome and other troublesome grass weeds (Young, Whaley, Lawrence, & Burke, 2016) that are common with the monoculture WW–F system.

Although the vast majority of reports in the literature document positive effects of including canola in wheat-based rotations, a 6-yr study in eastern Washington showed that grain yield of spring wheat was reduced by an average of 17% after WC vs. WW (Schillinger & Paultiz, 2018). Surface soil samples were collected every year of the study to determine microbial biomass and community composition using phospholipid fatty acid analysis (PLFA). The WC-associated microbial community contained significantly less fungi, mycorrhizae, and total microbial biomass than WW (Hansen, Schillinger, Sullivan, & Paulitz, 2019). Other related long-term studies on canola in wheat-based rotations are ongoing.

3.2 | Private-sector and government advances and incentives to grow canola

The rapid adoption of WC by farmers in the drylands has been expedited by the opening of major canola seed processing facility in 2013 near the town of Warden in central Washington in combination with a major extension

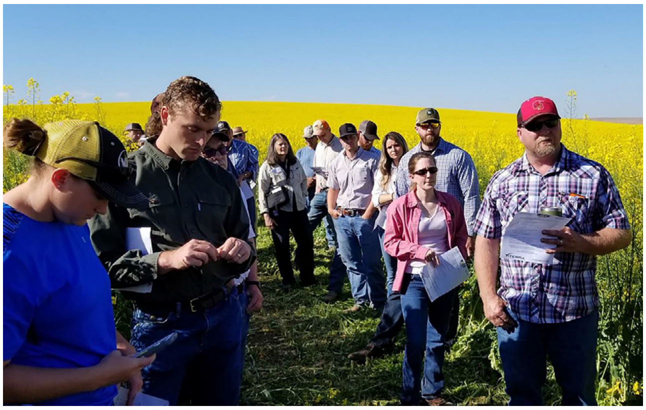

FIGURE 9 Canola land area in the Inland Pacific Northwest has increased substantially in the past decade driven by construction of a large canola crushing facility in Warden, WA, and an effective extension outreach program by Washington State University through the Washington Oilseeds Cropping Systems Project. (Photo credit: Karen Sowers)

outreach program by Washington State University (Figure 9; WOCS, 2020). The Warden facility is the largest canola processing plant West of the Rocky Mountains with capacity to crush more than 350,000 Mg of canola annually to produce more than 135,000 Mg of canola oil. Non-GMO canola is food-grade quality and can also be used for biodiesel feedstock. The market for GMO canola is for renewable energy. Before the advent of this large crushing facility, canola was shipped to North Dakota or Canada for processing. To date, canola production throughout the PNW is not adequate to meet the capacity of the Warden plant and the shortfall of canola seed is imported from North Dakota and Canada.

Private-sector and university breeding programs have made rapid progress in the past 15 yr developing both spring canola and WC cultivars with unique characteristics and tolerances. Most wheat farmers in the PNW drylands use soil-residual herbicides which includes the Group 2 ALS inhibitors sulfonylurea and imidazolinone (Nakka, Jugulam, Peterson, & Asif, 2019). Soil carryover of these herbicides can continue for several years. New canola cultivars are available to farmers that are tolerant of the soil residuals from these herbicides. It is critical for farmers who intend to plant canola to know the herbicide history of the field for the past several years (Pan et al., 2016). Glyphosate [*N*-(phosphonomethyol)glycine]-tolerant canola cultivars are also available. Other advances for WC include cultivars with winter cold tolerance almost as good as some WW cultivars.

The Washington State Legislature passed a law (RCW 19.112.110, 2006) in 2006 that requires that at least 2% of diesel sold within the state must be biodiesel. Canola oil is considered the most important *Brassica* oilseed for this biodiesel feedstock. This law further mandates that at least 5% of diesel must be biodiesel when the state's Department of Agriculture determines that in-state production of oilseed feedstock can satisfy this requirement.

3.3 | Winter canola establishment

By far the biggest challenge for WC production in the drylands is stand establishment. Adequate seed-zone moisture in fallowed fields in August and early September is often located 12 cm or deeper below the soil surface. Although planting with a deep-furrow drill (Figure 4) stacks some of the dry soil on the furrow ridge (to reduce the thickness of the soil covering the seed), the distance from seed placement to soil surface within the furrow should not exceed 5 cm soil (Pan et al., 2016). In addition to soil depth, WC emergence is highly affected by soil surface temperature. Maximum air temperature should not exceed 30 °C on Days 5–8 after planting when emerging WC seedlings near the dry soil surface. The temperature of the surface 2–3 cm of soils in August is often >10 °C warmer than air temperature. The elongating hypocotyl of WC is extremely sensitive to high surface-soil temperatures.

In the author's opinion, the highest probability of achieving a stand of WC is to practice chem fallow and hope for a local thunderstorm that delivers at least 13 mm of rain sometime between 1 August and 15 September (Figure 10). One hundred years of accurate U.S. National Weather Bureau records at Lind, WA, show that there is, on average, a 22% chance of receiving 13 mm or more rain within any given 2-d period during this time. This makes WC an "opportunity crop" for most PNW dryland farmers.

3.4 | Dual-purpose winter canola

An alternative to planting WC in August or early September is to plant in late June or early July when soil moisture in chem fallow is still close to the soil surface. However, if WC is established this early, plants will grow quite large and use all available moisture in the soil profile by September (Reese, 2015) and likely not survive the ensuing winter. Farmers and scientists are currently evaluating grazing of early-planted WC in August and September to provide a food source for cattle, reduce soil moisture extraction by WC, and benefit over-winter WC survival (Figure 11). Dual-purpose grazing of canola has been successfully practiced in Australia (Lilley, Bell, & Kirkegaard, 2015) and other areas of the world but the success of this method has not yet been documented in the PNW drylands.

FIGURE 10 Excellent stand of winter canola (WC) that was planted into winter wheat stubble after 13 mo of chem fallow. Stand establishment is the major issue with WC because of its small seed. Adequate seed-zone moisture in late summer is frequently located 12 cm or deeper in the soil profile. Many farmers in the drylands view WC as an opportunity crop to be planted after an occasional late-summer thunderstorm delivers 13 mm or more rain to wet the dry soil down to the wetting zone of fallow; referred to as "wetting up" by farmers. Long-term weather records show there is a 22% likelihood of receiving such a substantial rain event within a 1-to 2-d period between 1 August–15 September. (Photo credit: Karen Sowers)

FIGURE 11 Dual-purpose winter canola (WC). Winter canola can generally be easily established in late June when near-surface soil moisture is still present in fallow ground. Grazing in August and September provides a food source for cattle and the grazed WC then resumes growth in the spring and is harvested in July. Otherwise, WC planted in late June will grow too big, use all available soil moisture by September, and likely die during the ensuing winter. (Photo credit: Karen Sowers)

3.5 | Attitude of farmers about winter canola

Farmers in the PNW drylands have planted ever increasing land area of WC in the past 10 yr (USDA-NASS, 2019b). Private and public breeding programs have released WC cultivars with increased winter hardiness and resistance to commonly used soil-residual herbicides. Washington State University has had an effective and active extension oilseeds specialist since 2007. Growing WC provides farmers an excellent opportunity to control grass weeds. Many farmers believe they receive a 20% yield boost in grain yield of wheat after canola vs. wheat after wheat, however, long-term experiments have not yet documented this enhancement. The large canola-crushing facility in Warden, WA, provides a nearby delivery location.

By far the biggest challenge for WC production in the PNW drylands is stand establishment (see Section 3.3). Most farmers who grow WC believe it to be more profitable than WW. Market price is of course a factor. The market price for canola in eastern Washington in the past 10 yr has ranged from \$309 to \$529 Mg^{-1} (NASS, 2019).

4 | WINTER TRITICALE

Triticale is a cereal produced by crossing wheat with the rye (*Secale cereale* L.). Both forage and grain types of triticale cultivars are grown. The focus here is grain triticale. The latest U.S. agricultural census conducted in 2017 reported that triticale grain was harvested from 33,000 ha with 3,700 ha of the total from the state of Washington (USDA-NASS, 2017). Triticale grain is primarily used as a feed for pigs, poultry, and ruminants as it is a good source of protein, amino acids, and B vitamins (Zhu, 2018). The grain as well as the straw of triticale are important feedstocks for production of ethanol and biogas (Beres et al., 2013). Triticale has better tolerance to both saline and acidic soil conditions, is less susceptible to many fungal diseases, and has better winter cold hardiness than wheat (Blum, 2014; Cantale et al., 2016; GRDC, 2018). There are many reports in the literature that triticale consistently produces higher grain yields compared to wheat (Bassu, Asseng, & Richards, 2011; Giunta, Motzo, & Pruneddu, 2003). Farmers in the dryland PNW consider WT to be tougher and even more "bullet proof" than WW.

4.1 | Recent long-term winter triticale cropping systems study at Ritzville, WA

The agronomic and economic results of a 9-yr WT cropping systems experiment conducted near Ritzville, WA, were

FIGURE 12 Winter triticale (WT) grown in individual 9 by 150 m (0.135 ha) plots at the long-term cropping systems experiment near Ritzville, WA. Grain yield of this WT crop was 5,533 kg ha^{-1}. Over 9 yr, grain yield of WT ranged from 4,245 to 7,426 kg ha^{-1} and averaged 5,816 kg ha^{-1}. (Photo credit: W. F. Schillinger)

FIGURE 13 Early-planted winter wheat (WW, left) and early-planted winter triticale (WT, right) ripe for harvest at the long-term cropping systems experiment near Ritzville, WA. Averaged over 9 yr, WT produced 14% more grain than WW. The higher grain yield achieved by WT was due to greater number of kernels $spike^{-1}$ and heavier kernel weight despite having much fewer spikes m^{-2} compared to the WW. (Photo credit: W. F. Schillinger)

recently compiled (W. Schillinger & D. Archer, unpublished data). This study was conducted on the same farm as the winter pea experiment reported in Section 2.3. The study was part of a large-scale and long-term dryland cropping systems experiment where three crop rotations were compared. These were: (a) 3-yr WT–SW–F; (b) 3-yr WW–SW–F; and (c) 2-yr WW–F. Experimental design was a randomized complete block with four replications. Individual plot size was 9 by 150 m (Figures 5 and 12). All phases of all rotations were present every year for a total of 32 plots. Measurements included grain yield, grain yield components, straw production, soil water dynamics, and effect on the subsequent spring wheat crop. Enterprise budgets were constructed to determine production costs and profitability of the rotations.

Grain yields averaged over the 9 yr were 5,816; 5,087; and 4,689 kg ha^{-1} for WT, 3-yr WW, and 2-yr WW, respectively. The higher grain yield achieved by WT was due to greater number of kernels/spike and heavier kernel weight despite having much fewer spikes m^{-2} compared to the WW treatments (Figure 13).There were no differences in straw production between WT and WW. There are many reports in the literature that WT produces more straw than WW, but these statements were based on visual observations and not properly quantified. Winter wheat produced significantly more stems than WT, but this was compensated by individual stem weight of WT being 60% heavier than that of WW. Winter triticale used slightly but significantly less water that WW and WT stubble provided higher overwinter precipitation storage efficiency in the soil compared to WW stubble. Spring wheat yield averaged 2,451 vs. 2,322 kg ha^{-1} after WT and WW, respectively.

The market price for triticale grain was always less than that for wheat. However, WT produced an average of 14 and 24% more grain than 3- and 2-yr WW, respectively, and provided rotation benefits. Economic assessment showed that the WT rotation was less profitable than the two WW rotations. An increase in WT price (or a corresponding boost in WT grain yield) would have been necessary for the WT rotation to be as profitable as the WW rotations (W. Schillinger & D. Archer, unpublished data).

4.2 | Early vs. late planting dates for winter triticale and winter wheat at Lind, WA

4.2.1 | Study description

A 5-yr field study was conducted during the 2015–2019 crop years at the WSU Lind Dryland Research Station to determine early- vs. late-planting date effects on WT and WW grain yield. Late planting of WW in mid-to-late October is known to reduce grain yield by at least 35% compared to WW planted in late August–early September (Higginbotham, Jones, & Carter, 2011). On the other hand, farmers and researchers had observed that late-planted WT appeared to have less yield drag compared to early-planted WT. Could WT possibly be a better alternative than WW in dry years when early planting deep into carryover soil moisture is not possible and farmers must wait until the onset of rain in mid-October or later to establish their crops?

TABLE 2 Grain yield of early- and late-planted winter triticale (WT) compared to early- and late-planted winter wheat (WW) for 5 yr at Lind, WA. Early planting was the last week in August and late planting was mid-October. Seeding rate for both WT and WW was 140 seeds m^{-2} for early planting and 245 seeds m^{-2} for late planting

Crop	2015	2016	2017	2018	2019	5-yr avg.
	Grain yield, kg ha^{-1}					
Early-planted WT	1,775a	3,795a	5,475a	5,095a	3,455a	3,920a
Late-planted WT	1,575ab	3,775ab	2,805c	3,005c	2,235b	2,680c
Early-planted WW	1,745ab	3,345ab	4,070b	4,210b	3,250a	3,325b
Late-planted WW	1,535b	3,320b	2,425c	2,235d	1,750b	2,250d
Significance (*P* value)	.047	.012	<.001	<.001	<.001	<.001
	Crop-year precipitation, mm[a]					
	193	322	375	310	223	285

[a] Crop-year precipitation at Lind from 1 September–31 August.

Long-term (100-yr) average annual precipitation at the Lind site is 244 mm whereas average pan evaporation from April through September is 1,412 mm. Crop-year (1 September–31 August) precipitation during the study period ranged from 193 to 375 mm and averaged 285 mm (Table 2). The soil is Shano silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids) with uniform texture and no rocks within the 180-cm profile. Shano soils are common throughout much of the low-precipitation cropping region of east-central Washington.

Experimental design was a randomized complete block and treatments were replicated six times for a total of 24 plots. Treatments were: (a) early-planted WT, (b) early-planted WW, (c) late-planted WT, and (d) late-planted WW. All treatments were seeded into ground that had been left fallow for at least 13 mo. Individual plot size was 2.5 by 30 m. Early-planted WT and WW were sown on the same day during the last week of August at a rate of 140 seeds m^{-2} with a deep-furrow drill (Figure 4) that placed seeds deep into moisture with an average of 13 cm of soil covering the seed. Late-planted WT and WW was sown shallow with 3 cm of soil covering the seed at a rate of 245 seeds m^{-2} with a hoe-opener drill with 10 cm paired rows on 30-cm row spacing. The WT cultivar Trimark 099 and WW cultivar Otto were used every year. All seed was treated with a broad-spectrum fungicide + insecticide for wireworm (*Agriotes lineatus*) control. Satisfactory plant stands were achieved for all four treatments in all 5 yr.

4.2.2 | Results and discussion

Grain yield data for the study are shown in Table 2. Early WT produced numerically greater yield that early WW every year and significantly greater yield in 2 yr as well as the 5-yr average ($P < .0001$). Late WT and WW produced significantly lower yield than their early-planted counterparts in 3 yr as well as the 5-yr average ($P < .0001$, Table 1). Late WT significantly out yielded late WW in only 1 yr, but the 5-yr average yield difference was highly significantly different ($P < .0001$).

Rainfall and air temperature in the months of May and June likely had a large impact on grain yield. Grain yields of all treatments were low in 2015 when only 193 mm of precipitation fell during the entire crop year. There was zero precipitation in the month of June with five successive days of 33–37 °C heat in early June and another four straight days of 38–42 °C heat later in June. Grain yield among treatments was also quite similar in 2016 with mild air temperatures and well above-normal rainfall in May, but this was followed by 5 d of 34–37 °C temperatures at the beginning of June.

The largest (32%) grain yield advantage of early WT vs. early WW was in 2017 (Table 2) with three consecutive days of 32–35 °C air temperatures in late May when early WW was at its peak of anthesis whereas anthesis of early WT was completed by that date. A somewhat similar situation occurred in 2018 which resulted in early WT producing 21% more grain than early WW.

To summarize this experiment over the 5 yr:

1. Early WT produced 15% more grain yield than early WW.
2. Late WT produced 16% more grain yield than late WW.
3. Early WT produced 32% more grain yield than late WT.
4. Early WW produced 32% more grain yield than late WW.

The 15% yield increase of early WT over early WW is similar to that in the 9-yr WT cropping systems study at Ritzville summarized in Section 4.1. Thus, with current and historic grain prices, WT is not economically competitive with WW.

The grain yield of both late WT and late WW lagged their early-planted counterparts by an average of 32%. These data reinforce the long-understood fact that WW (and now understood for WT) must be planted in late August–early September to achieve optimum yield potential.

4.3 | Attitude of farmers about winter triticale

Farmers in the PNW drylands know that WT is easy to grow and is hardy. Whereas, winterkill of WW in east-central Washington occurs about once every 15 yr, no winterkill of WT has ever been reported. Farmers routinely apply one (and sometimes two) in-crop applications of fungicide to WW in the spring to control stripe rust *(Puccinia striiformis* f.sp. *tritici*) whereas, to date, no stripe rust control has been required for WT. Winter triticale is ripe for cutting at least 7 d before WW which allows farmers to spread their harvest workload more efficiently over time. Recently, a small group of dryland farmers, university faculty, and agricultural industry personal led a successful lobbying effort to obtain subsidized federal crop insurance for WT in the PNW. Their main argument was that triticale is tough, has stable and high yields, and is one of the very few alternatives to monoculture WW–F. The grain yields from the Ritzville long-term WT cropping systems study (see Section 4.1) was used to document "proven yields". Federal crop insurance was subsequently made available for triticale production in the PNW as well as other regions of the United States (USDA-FCIC, 2017), thus providing farmers the same safety net insurance as that available for WW, WC, and WP.

Some dryland farmers have expressed concern that WT may become a weed because cereal rye is the male parent of triticale. "Feral" cereal rye diverged from domesticated cereal rye in the 1950s. Feral rye has secondary seed dormancy which allows seed to lay dormant for one or more years before germinating (Roerig & Ronsom, 2017) and requires hand roughing or herbicide "rope wicking" for in-crop control in WW. However, triticale seed has no secondary dormancy and, like wheat, does not persist in the seed bank (Raatz, Yang, Beres, & Hall, 2012). Therefore, the concern by some PNW farmers that WT will become a "feral" weed is unfounded.

The bottom line for farmers is, of course, economics. Despite having significantly greater grain yield than WW, the market price for triticale is less than for wheat. Winter triticale, to date, has not required a fungicide application but this and other rotational benefits of WT over WW were factored into the economic analysis by W. Schillinger and D. Archer (unpublished data) (see Section 4.1). Besides use as an animal feed grain, triticale grain is also used by liquor distilleries and in some bread products; thus, the market value of triticale grain could increase in time.

5 | SUMMARY

The 2-yr WW–F rotation practiced for more than 130 yr has provided relatively stable grain yields and profits for farmers in the drylands of east-central Washington. This monoculture system has also created several problems, including winter annual grass weed infestations that are increasingly difficult to control. Growing spring-planted crops helps to control these grass weeds, but all spring crops so far evaluated have demonstrated wide year-to-year variability in grain yield and have not been profitable in the long term.

Over the past 10–15 yr, experience by farmers and researchers has shown that WP, WC, and WT have excellent promise in the drylands. Like WW, all three of these crops need to be planted in late summer into stored soil moisture after a 13-mo fallow to achieve optimum yield potential. Winter pea and WC are broadleaf crops that allow for in-crop grass weed control and provide additional benefits. Land area planted to WP, WC, and WT is increasing as farmers learn about, and become more comfortable, growing these crops.

This article is a tribute to Dr. B. A. Stewart for his legendary contributions to our understanding of crops and soils in dry environments. He is well deserving of special recognition in this issue of *Agronomy Journal* to honor this legacy. Dr. Stewart would likely have felt right at home had he spent his career as an agronomist and soil scientist in the often harsh, but always interesting, dryland cropping region of the PNW.

ACKNOWLEDGMENTS

Funding for the studies reported in this paper was provided by the USDA National Institute of Food and Agriculture through Hatch project 1017286, the Regional Approaches to Climate Change (REACCH) project, and the Landscapes in Transition (LIT) project. Additional funding was provided by the Washington Oilseeds Cropping Systems (WOCS) project and by ProGene Plant Research. The cooperation and support by collaborating farmers Ron Jirava and Bruce Sauer is gratefully acknowledged. Excellent field and office support were provided by John Jacobsen, Steve Schofstoll, and Samantha Crow located at the Washington State University Lind Dryland Research Station. Special thanks to Howard Nelson; Highline Grain Growers, Inc.; and Rebecca McGee, USDA-ARS for their valuable personal communications with the author on winter pea.

FOREWORD

This article is a tribute to Dr. B. A. Stewart for his 60+ yr of research and service to promote the betterment of dryland cropping in the U.S. Southern Great Plains and around the world. Dr. Stewart has a lifelong reputation for research excellence in crop and soil management, water quality and other related topics. He has been referred to as "the best of the best" for his leadership and mentoring of local, national, and international research efforts. Bob is often referred to as "Dr. Dryland" and it is an honor to provide this tribute article to him and his legacy from the low-precipitation dryland cropping region of the U.S. Pacific Northwest.

CONFLICTS OF INTEREST

The author declares that there is no conflicts of interest.

ORCID

William F. Schillinger https://orcid.org/0000-0001-9285-8159

REFERENCES

Agriculture and Agri-Food Canada. (2019). *Canada: Outlook for principal food crops*. Ottawa, ON: Agricultural and Agri-Food Canada.

Angus, J. F., Kirkegaard, J. A., Hunt, J. R., Ryan, M. H., Ohlander, L., & Peoples, M. B. (2015). Break crops and rotations for wheat. *Crop & Pasture Science*, *66*, 523–552.

Arshad, M. A., Soon, Y. K., & Azooz, R. H. (2002). Modified no-till and crop sequence effects on spring wheat production in northern Alberta, Canada. *Soil & Tillage Research*, *65*, 29–36.

Bassu, S., Asseng, S., & Richards, R. (2011). Yield benefits of triticale traits for wheat under current and future climates. *Field Crops Research*, *124*, 14–24.

Beres, B., Pozniak, C., Eudes, F., Graf, R., Randhawa, H., Salmon, D., … Spaner, D. (2013). A Canadian ethanol feedstock study to benchmark the relative performance of triticale: 1. Agronomics. *Agronomy Journal*, *105*, 1695–1706.

Blum, A. (2014). The abiotic stress response and adaption of triticale – a review. *Cereal Research Communication*, *42*, 359–375.

Busacca, A. J. (1991). Loess deposits and soils of the Palouse and vicinity. In R. B. Morrison (Ed.), *Quaternary non-glacial geology of the United States* (pp. 216–228). Decade of North American Geology Series Volume K-2. Boulder, CO: Geological Society of America.

Bushong, J. A., Griffith, A. P., Peeper, T. F., & Eppling, F. M. (2012). Continuous winter wheat versus a winter canola-winter rotation. *Agronomy Journal*, *104*, 324–330.

Cantale, C., Petrazzuolo, F., Correnti, A., Farneti, A., Felici, F., Latini, A., & Galeffi, P. (2016). Triticale for bioenergy production. *Agriculture & Agricultural Science Proceedings*, *8*, 609–616.

Chen, C., Miller, P., Muehlbauer, F., Neill, K., Wichman, D., & McPhee, K. (2006). Winter pea and lentil response to seeding date and micro- and macro-environments. *Agronomy Journal*, *98*, 1655–1663.

Giunta, F., Motzo, F., & Pruneddu, G. (2003). Comparison of temperate cereals and grain legumes in a Mediterranean environment. *Agricoltura Mediterranea*, *133*, 234–248.

GRDC. Grains Research & Development Corporation. (2018). *Triticale: Diseases*. Section 9. Canberra, Australia: Grains Research & Development Corporation. Retrieved from https://grdc.com.au/resources-and-publications/grownotes/crop-agronomy/triticalegrownotessouthern

Hansen, J. C., Schillinger, W. F., Sullivan, T. S., & Paulitz, T. C. (2019). Soil microbial biomass and fungi reduced with canola introduced into a long-term monoculture wheat rotations. *Frontiers in Microbiology*, *10*, 1488.

Harris, R. H., Scammell, G. J., Miller, W. J., & Angus, J. F. (2002). Crop productivity in relation to species of previous crops and management of previous pastures. *Australian Journal of Agricultural Research*, *53*, 1271–1283.

Higginbotham, R. W., Jones, S. S., & Carter, A. H. (2011). Adaptability of wheat cultivars to a late-planted no-till fallow production system. *Sustainability*, *3*, 1224–1233.

Huggins, D., Pan, B., Schillinger, W., Young, F., & Machado, S. (2015). Crop diversity and intensity in Pacific Northwest dryland cropping systems. In K. Borrelli, D. Daily, S. Laursen, S. Eigenbrode, B. Mahler, & R. Pepper (Eds.), *Regional approaches to climate change for Pacific Northwest agriculture. Climate science Northwest farmers can use* (pp. 38–41). Moscow, ID: University of Idaho. Retrieved from www.reacchpna.org

Juergens, L. A., Young, D. L., Schillinger, W. F., & Hinman, H. R. (2004). Economics of alternative no-till spring crop rotations in Washington's wheat-fallow region. *Agronomy Journal*, *96*, 154–158.

Karimi, T., Stöckle, C. O., Higgins, S. S., Nelson, R. L., & Huggins, D. (2017). Projected dryland cropping system shifts in the Pacific Northwest in response to climate change. *Frontiers in Ecology & Evolution*, *5*, 20.

Kirby, E., Pan, W., Huggins, D., Painter, K., & Bista, P. (2017). Rotational diversification and intensification. In G. Yorgey & C. Kruger (Eds.), *Advances in dryland farming in the Pacific Northwest* (pp. 163–236). EM108. Pullman, WA: Washington State University Extension. Retrieved from http://pubs.cahnrs.wsu.edu/publications/pubs/em108/

Kirkegaard, J., Christen, O., Krupinsky, J., & Layzell, D. (2008). Break crop benefits in temperate wheat production. *Field Crops Research*, *107*, 185–195.

Krupinsky, J. M., Tanaka, D. L., Merrill, S. D., Liebig, M. A., & Hanson, J. D. (2006). Crop sequence effects of 10 crops in the northern Great Plains. *Agricultural Systems*, *88*, 227–254.

Lilley, J. M., Bell, L. W., & Kirkegaard, J. A. (2015). Optimising grain yield and grazing potential of crops across Australia's high-rainfall zone: A simulation analysis. 2. Canola. *Crop & Pasture Science*, *66*, 349–364.

Long, D. S., Young, F. L., Schillinger, W. F., Reardon, C. L., Williams, J. D., Allen, B. L., … Wysocki, D. J. (2016). Development of dryland oilseed production systems in Northwestern region of the USA. *Bioenergy Research*, *9*, 412–429.

Maaz, T., Wulfhorst, J. D., McCracken, V., Kirkegaard, J., Huggins, D. R., Roth, I., … Pan W. (2018). Economic policy, and social trends and challenges of introducing oilseed and pulse crops into dryland wheat cropping systems. *Agriculture Ecosystems & Environment*, *253*, 177–194.

Machado, S., Rhinhart, K., & Petrie, S. (2006). Long-term cropping system effects on carbon sequestration in eastern Oregon. *Journal of Environmental Quality*, *35*, 1548–1553.

McPhee, K. E., Chen, C. C., Wichman, D. M., & Muehlbauer, F. J. (2007). Registration of 'Windham' winter feed pea. *Journal of Plant Registrations*, *1*, 117–118.

Miller, P. R., Bekkerman, A., Jones, C. A., Burgess, M. H., Holmes, J. A., & Engel, R. E. (2015). Pea in rotation with wheat reduced uncertainty of economic returns in southwest Montana. *Agronomy Journal*, *107*, 541–550.

Miller, P. R., Gan, Y., McConkey, B. G., & McDonald, C. L. (2003). Pulse crops for the Northern Great Plains: II. Cropping sequence effects on cereal, oilseed, and pulse crops. *Agronomy Journal*, *95*, 980–986.

Nakka, S., Jugulam, M., Peterson, D., & Asif, M. (2019). Herbicide resistance: Development of wheat production systems and current status of resistant weeds in wheat cropping systems. *Crop Journal*, *7*, 750–760.

Nelson, H. (2017). *Central Washington grain growers 2016 test plot results*. Retrieved from http://www.cwgg.net/images/603/2016TestPlotResults.pdf

Pacific Northwest Canola Association. (2019). *Where is it grown?* https://pnwcanola.org/for-consumers/where-is-it-grown/

Pan, W.F., Young, F. L., Maaz, T. M., & Huggins, D. R. (2016). Canola integration into semi-arid wheat cropping systems in the inland Pacific Northwestern USA. *Crop & Pasture Science*, *67*, 253–265.

Papendick, R. I. (2004). *Farming with the wind II: Wind erosion and air quality control on the Columbia Plateau and Columbia Basin*. Special Report by the Columbia Plateau PM_{10} Project. Report XB 1042. Pullman, WA: Washington Agriculture Experiment Station. Retrieved from https://pnw-winderosion.wsu.edu/publications/farming-with-the-wind-ii/

Raatz, L. L., Yang, R-C., Beres, B. L., & Hall, L. M. (2012). Persistence of triticale seed in the soil seed bank. *Crop Science*, *52*, 1868–1880.

RCW 19.112.110. (2006). *Motor fuel quality act*. Washington State Legislature. Retrieved from http://apps.leg.wa.gov/rcw/default.aspx?cite19.112&fulltrue

Reese, M. (2015). *Dryland winter canola water and nitrogen use in eastern Washington*(Master's of Science thesis, Washington State University). Retrieved from http://www.dissertations.wsu.edu/Thesis/Fall2015/m_reese_120115.pdf

Roerig, K. C., & Ransom, C. V. (2017). Expansion of feral cereal rye (*Secale cereale* L) on non-crop hillsides in northern Utah. *Invasive Plant Science Management*, *10*, 26–32.

Schillinger, W. F. (2017). Winter pea: Promising new crop for Washington's dryland wheat-fallow region. *Frontiers in Ecology & Evolution*, *5*, 43.

Schillinger, W. F., & Papendick, R. I. (2008). Then and now: 125 years of dryland wheat farming in the Inland Pacific Northwest. *Agronomy Journal*, *100*, S–166–S–182.

Schillinger, W. F., Papendick, R. I., Guy, S. O., Rasmussen, P. E., & van Kessel, C. (2006). Dryland cropping in the western United States. In G. A. Peterson, P. W. Unger, & W. A. Payne (Eds.), *Dryland agriculture*(2nd ed., pp. 365–393). Madison, WI: ASA, CSSA, and SSSA.

Schillinger, W. F., & Paulitz, T. C. (2018). Canola versus wheat rotation effects on subsequent wheat yield. *Field Crops Research*, *223*, 26–32.

Sharratt, B., Feng, G., & Wendling, L. (2007). Loss of soil and PM_{10} from agricultural fields associated with high winds on the Columbia Plateau. *Earth Surfaces Processes & Landforms*, *32*, 621–630.

Sharratt, B. S., Kennedy, A. C., Hansen, J. C., & Schillinger, W. F. (2018). Soil carbon loss by wind erosion of summer-fallowed fields in Washington's dryland wheat region. *Soil Science Society of America Journal*, *82*, 1551–1558.

Smith, B. J., & Kirkegaard, J. A. (2002). In vitro inhibition of soil microorganisms by 2-phenylethyl isothiocyanate. *Plant Pathology*, *51*, 585–593.

Smith, B. J., Kirkegaard, J. A., & Howe, G. N. (2004). Impacts of Brassica break crops on soil biology and yield following wheat crops. *Australian Journal of Agricultural Research*, *55*, 1–11.

Stöckle, C. O., Higgins, S., Nelson, R., Abatzoglou, J., Huggins, D., Pan, W., … Brooks, E. (2018). Evaluating opportunities for an increased role of winter crops as adaptation to climate change in dryland cropping systems of the US Inland Pacific Northwest. *Climate Change*, *146*, 247–261.

USDA-FCIC. (2017). *Triticale crop insurance standards handbook*. FCIC-2031U (06-2017). Washington, DC: U.S. Department of Agriculture-Federal Crop Insurance Corporation.

USDA-NASS. (2017). *2017 Agricultural census*. Washington, DC: U.S. Department of Agriculture-National Agricultural Statistics Service.

USDA-NASS. (2019a). *Dry pea area planted and harvested*. Washington, DC: U.S. Department of Agriculture-National Agricultural Statistics Service.

USDA-NASS. (2019b). *Canola area planted and harvested*. Washington, DC: U.S. Department of Agriculture-National Agricultural Statistics Service.

Williams, C. M., King, J. R., Ross, S. M., Olson, M. A., Hoy, C. F., & Lopetinsky, K. J. (2014). Effects of three pulse crops on subsequent barley, canola, and wheat. *Agronomy Journal*, *106*, 343–350.

WOCS. (2020). *Washington oilseeds cropping systems project*. Pullman, WA: Washington State University. Retrieved from http://css.wsu.edu/oilseeds/

Young, F. L., Alldredge, J. R., Pan, W. L., & Hennings, C. (2015). Comparisons of annual no-till cereal cropping systems in the Pacific Northwest. *Crop Forage & Turfgrass Management*, *1*, 1–7.

Young, F. L., & Thorne, M. E. (2004). Weed-species dynamics and management in no-till and reduced-till fallow cropping systems for the semi-arid agricultural region of the Pacific Northwest, USA. *Crop Protection*, *23*, 1097–1110.

Young, F. L., Whaley, D. K., Lawrence, N. C., & Burke, I. C. (2016). Feral Rye (*Secale cereal*) control in winter canola in the Pacific Northwest. *Weed Technology*, *30*, 163–170.

Zhu, P. (2018). Triticale: Nutritional composition and food uses. *Food Chemistry*, *241*, 468–479.

Zuzel, J. F. & Pikul, J. L. (1987). Infiltration into a seasonally frozen agricultural soil. *Journal of Soil & Water Conservation*, *42*, 447–450.

How to cite this article: Schillinger WF. New winter crops and rotations for the Pacific Northwest low-precipitation drylands. *Agronomy Journal*. 2020;112:3335–3349. https://doi.org/10.1002/agj2.20354