Chapter 5

Rotational Diversification and Intensification

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Abstract

Diversification and intensification of inland Pacific Northwest (PNW) dryland cereal cropping systems can present win-win scenarios that deliver short and long-term benefits for producers and the environment, stabilizing profit and increasing adaptability to and mitigation of climate change. Improving diversity, or reducing fallow, can enhance current farm productivity and income levels, pest management, soil structure, and water infiltration. Alternating oilseeds and grain legumes, in rotation with cereals, can reduce greenhouse gas emissions and improve nitrogen cycling; replacing fallow with crops can increase straw residues and the potential for carbon sequestration. Growers seek reliable, site-specific information on the management and potential of alternative cash crops and cover crops. Recent studies help to interpret the agronomic and economic feasibility of alternative cropping systems as well as understanding their role in potential climate change adaptation and mitigation.

Research results are coded by agroecological class, defined in the glossary, as follows:

● Annual Crop ▲ Annual Crop-Fallow Transition ■ Grain-Fallow

Key Points

- Rotational diversity is low in the wheat-dominated cereal production systems of the inland PNW. Diversifying or intensifying cropping systems helps producers minimize lost production opportunities, improve farm productivity, increase grower income and flexibility, adapt to predicted climate change, and achieve long-term environmental benefits.
- Adopting alternative rotations comes with tradeoffs and can increase risk. Success is dependent on geographic location, production potential, rotational fit, market opportunity, crop price, and production costs.
- Broadleaf crop sequences can improve cereal pest management, nutrient cycling, or soil structure. For example, legumes can reduce nitrogen fertilizer costs and greenhouse gas emissions and canola can increase water infiltration, break up hardpans, disrupt weed and disease cycles, and access water and nutrients deep in the soil.
- Adopting improved fallow practices can be an important step toward building soil resiliency and increasing future opportunity for diversification and intensification in tilled grain-fallow systems.
- Rotational benefit to wheat yield should be accounted for when evaluating potential returns for alternate crop rotations.

Introduction

Wheat has been the dominant crop in the **inland PNW** dryland region since land was first broken out of native bunchgrass and sagebrush. Cool season small grain cereals are well-suited to the region and the development and adoption of locally adapted, semi-dwarf varieties along with access to chemical fertilizers and pesticides have made it possible to grow wheat profitably for long periods. However, intensive tillage and fallow-based production have contributed to degraded **soil health** and declining productivity. Growers are increasingly interested in rotational diversification with alternate crops and intensification strategies such as fallow replacement, increased cropping with alternate winter crops, and **cover cropping**. These strategies target improved long-term productivity and more flexible adaptation to ongoing and predicted climate change.

Acronyms Used in Crop Rotations

AWP – Austrian winter pea
ChF – chemical fallow
CP – chickpea
F – fallow
FB – facultative barley
FW – facultative wheat
HRSW – hard red spring wheat
HRWW – hard red winter wheat
L – spring lentil
P – spring pea
SAF – safflower
SB – spring barley
SC – spring canola
SW – spring wheat
SWSW – soft white spring wheat
SWWW – soft white winter wheat
UTF – undercutter tillage fallow
WC – winter canola
WL – winter lentil
WP – winter pea
WT – winter triticale
WW – winter wheat

The region's climate, topography, and soils are highly diverse, yet crop diversity remains low, particularly in the driest areas where winter wheat-fallow has been the most profitable rotation. Cropping systems that lack diversity are more vulnerable to changes in commodity prices, production costs, and weather and climate. Strategies that increase diversity and intensification can provide growers greater flexibility, productivity, and income stability. Diversification is useful to break pest cycles, broaden pest management options, and manage herbicide resistance; crop sequences can be managed to increase carbon sequestration, reduce petroleum use, and mitigate greenhouse gas emissions. A broader selection of economically viable crops could advance the adoption of **no-till** cropping and decrease production costs, soil erosion, and degradation (Huggins and Reganold 2008; Kirkegaard et al. 2008a; Long et al. 2016; Pan et al. 2016).

Alternative crops have been evaluated in the inland PNW for more than 100 years (Figure 5-A1), but adoption has been limited by agronomic and economic challenges and government policy (Guy and Karow 2009; Kephart et al. 1990; Machado et al. 2004). Regional climate change, evolving markets, and more supportive government policies are motivating producers to further explore alternate crop options and maximize production opportunities. Heavy reliance on the volatile wheat market jeopardizes short-term profitability when wheat prices decline. Economic vulnerability is particularly evident in the drier regions where monocrop wheat systems dominate. Climate models predict warmer, drier summers, highlighting the need for flexibility and adaptation to increased temperature and drought stressors. Recent changes in federal farm support programs encourage more crop diversification; Farm Bill provisions encourage increased consumption of pulse crops and reduction of the farm energy footprint, providing incentives to produce grain legumes. Domestic consumption of dry pea, lentil, and chickpea (hummus) has increased from less than 0.5 pound to more than one pound per person since the early 1980s. Revisions to the US Standards for Whole Dry Peas and Split Peas and development of food quality varieties are broadening opportunities for growers to adopt winter peas. New federal insurance policies also help limit risk to producers as they develop alternative systems. In addition, the Energy Independence and Security Act of 2007 aimed to increase biofuel use and reduce petroleum consumption and greenhouse gas emissions has supported infrastructure and expanded opportunities for oilseed production in the inland PNW.

Recent research and grower efforts have focused on developing viable diversification strategies to further integrate oilseeds, grain legumes, alternate cereals, and cover crops into inland PNW cropping systems to improve agronomic, economic, and environmental performance, and to better understand their roles in adaptation to, or **mitigation** of, regional climate change. Producers face complex management decisions and assessment of potential benefits and tradeoffs. Greater crop choice would allow growers to better respond to commodity-driven opportunities and to plan crop choice and sequence in order to benefit wheat yield, **water use efficiency**, and nutrient cycling; enhance soil quality and residue management; or spread field workload. Successful diversification strategies will have a good agronomic fit, and meet short- and long-term economic and environmental goals. Crops must be adapted to local conditions, able to perform consistently, and not require extensive equipment modifications. In order to optimize these new crop rotations, alterations in other agronomic practices such as planting, soil and nutrient management, and harvesting techniques require re-evaluation.

Agroecological Class Characteristics, Production Challenges, and Adaptive Strategies

Three **agroecological classes** (AECs) are defined for the inland PNW dryland cereal production region based on the dominant cropping system and percentage of area in **fallow**: (1) Annual Crop (<10% fallow), (2) Annual Crop-Fallow Transition (10–40% fallow), and (3) Grain-Fallow (>40% fallow). Yield potential, limited by biogeographical factors and crop markets, determine the dominant cropping system and relative opportunities for diversification and intensification within each AEC (Huggins et al. 2015; Kaur et al. 2015). Biogeographical factors include climate (e.g., precipitation, potential evapotranspiration, temperature), soil characteristics (e.g., depth, texture, organic matter, soil water recharge, and **water holding capacity**), and topography. Cold, wet winters and warm to hot, dry summers are typical across the inland PNW. Areas with greater than 16” mean annual precipitation (MAP) can typically support annual cropping, whereas producers in drier areas rely on summer fallow practices for adequate recharge of soil water to support a subsequent crop. A map of the AECs and a description of the regional diversity, climate patterns, and precipitation and agronomic zone classifications are found in Chapter 1: Climate Considerations.

USDA National Agricultural Statistics Service (NASS) cropland layer data illustrate low crop diversity across the dryland AECs, discussed individually in the following chapter sections. The area of the Annual Crop AEC averaged 1.44 million acres from 2007 to 2014 compared to the Annual Crop-Fallow Transition and Grain-Fallow AECs with 1.85 and 2.52 million acres, respectively (Table 5-1). Predictably, crop diversity was greatest in the Annual Crop AEC and lowest in the Grain-Fallow AEC. Whereas opportunity for diversification varies by AEC, the fractions of crop area in winter wheat (40% to 45%) were fairly stable across the classes, indicating that growers make crop choices based on commodity opportunity rather than following set rotations. Crop diversity increased in all three AECs from 2007 to 2014. Spring pea and chickpea acreage increased in the Annual Crop and Transition AECs; lentil acreage declined from 2010 to 2014; the 2011 acreage drop-off represents lost cropping opportunities from excessively wet conditions that prevented

Table 5-1. Average percentage of crop and fallow area by agroecological class (2007–2014).

	Annual Crop ●	Transition ▲	Grain-Fallow ■	Total
Average million acres	1.44	1.85	2.52	5.81
Average % crop and fallow area				Crop acres
Fallow	3.2	27.6	50.1	1,822,796
Winter wheat	40.8	40.7	45.1	2,478,807
Spring wheat	16.6	15.8	2.8	599,657
Spring barley	5.5	4.4	0.4	169,884
Chickpea	6.8	0.6	0.03	109,115
Lentil	6.1	0.3	0	92,031
Pea	5.4	1.7	0.07	110,752
Canola	0.9	0.4	0.2	26,966
Alfalfa	5.4	5.3	0.8	197,614

Source: Unpublished values (Huggins pers. comm.) were compiled using NASS cropland layer data (2007–2015).

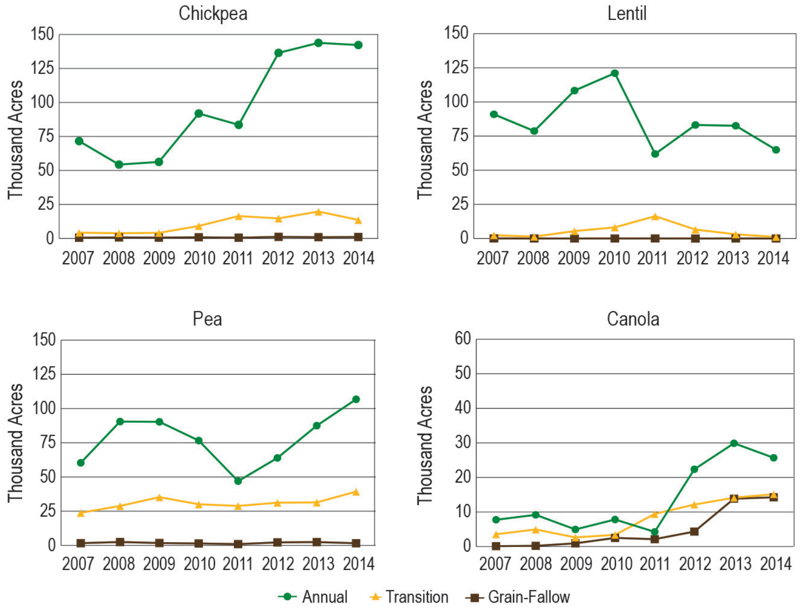

Figure 5-1. Annual grain legume and canola acreage trends by AEC (2007-2014). Unpublished values (Huggins pers. comm.) were compiled using NASS cropland layer data (2007-2015)

Table 5-2. Alternative crop sequences to improve rotational diversity by agroecological class.

	Traditional Sequences	Alternate Sequences
Annual Crop ●	WW-(SW or SB)- (P, L, or CP); WW-SW-WW-(P, L, or CP);	WW-SW-SC; WW-SW- (WP or WL); WW-SC-(P, L, or CP) back-to-back broadleaf
Transition ▲	WW-SW-F; WW-F	WW-SW-(WP or WL); WW-F-WC; WW-F-SC; WW-SW-SC; WW-SB-F
Grain-Fallow ■	WW-F	WW-F-WP; WW-F-WC; WW-F-WC-F; WW-F-WT-F

See Acronyms Used in Crop Rotations sidebar for abbreviation definitions.

Table 5-3. Diversification strategies by agroecological class.

	Traditional Sequences	Alternate Sequences
Annual Crop ●	• High productivity; heavy residue load • Steep slopes and erosion (water) • Reduced tillage • Persistent winter annual grass weeds • Cold wet springs (delayed or prevented planting)	• No-till • Winter legumes • Spring canola and other oilseeds • Herbicide-resistant canola • Cover crop • Perennial crops
Transition ▲	• Moderate productivity • Erosion (wind and water) • Deficient seed zone moisture • Reduced tillage • Persistent winter annual grass weeds • Areas of shallow soils	• No-till or improved fallow practices (e.g., tall cereals, stripper header, undercutter method) • Diversify • Flex crop (intensification) • Cover crop

Grain-Fallow ■	• Poor soil health; low productivity and residue
	• Reliance on fallow
	• Erosion (wind); fine, poorly aggregated soils
	• Deficient seed zone moisture
	• Intensive tillage
	• Persistent winter annual grass weeds
	• Marginal profitability
		• Diversify winter wheat phase
		  - Winter triticale or barley, pea or lentil, canola
		  - Facultative wheat or barley
		• Flex crop with adequate moisture
		  - Cereal or broadleaf
		• Improved fallow practices

planting spring crops. Canola acreage increased in all the dryland AECs (Figure 5-1).

Traditional and alternative rotations by AEC are listed in Table 5-2, and Table 5-3 summarizes production issues and adaptive strategies.

Annual Crop AEC ●

From 2007–2014, an average 63% of the Annual Crop AEC acreage was planted in small grain cereals including winter wheat (41%), spring wheat (17%), and spring barley (5%). Grain legumes (pea, lentil, and chickpea) accounted for 18% of the area, canola had nearly 1%, and just 3% of the area was in fallow (Table 5-1). Acreage of annual broadleaf crops increased nearly 50% during this period; chickpea acreage doubled to more than 140,000 acres, whereas canola acreage tripled, ranging from 22,000 to nearly 35,000 acres in 2012, 2013, and 2014 (Figure 5-1).

The Annual Crop AEC generally has sufficient available water to support continuous cropping and is characterized by high productivity and heavy post-harvest residue. Deep, silt loam soils can have up to 3–4% soil organic matter and 2.2–2.4 in/ft soil water holding capacity. Steep topography and winter precipitation make this region vulnerable to runoff and high rates of erosion. Exposed subsoil is common on hilltops and bare knobs, where productivity has been degraded. Improved wheat varieties and increased chemical inputs have helped maintain high yields in the region, and adoption of reduced tillage or no-till, including **direct seeding**, has helped to slow erosion and loss of soil organic matter (Douglas et al. 1999; Douglas et al. 1992; Schillinger et al. 2003; Schillinger and Papendick 2009). Wet, cold spring conditions can delay or even prevent planting; excessive residue keeps soils cool and wet, can hinder direct-seed practices, and favors soilborne pathogens. Annual grass weeds are a severe problem and can reduce yields by nearly half.

Growers commonly use 3- or 4-year crop sequences such as winter wheat-spring grain (wheat or barley)-spring legume and winter wheat-spring grain-winter wheat-spring broadleaf (legume or oilseed), shown in Table 5-2. Potential adaptive strategies include rotational diversification with no-till or reduced-till spring canola, winter peas or lentils, cover crops, and increased perennial plantings (Tables 5-2 and 5-3). Some growers are trying 4-year rotations including two consecutive years of broadleaf crops (e.g., WW-SC-P, L, or CP) to enhance weed management options. More specific information on integrating adaptive strategies is found in later sections of this chapter. Information on **conservation tillage** is presented in Chapter 3: Conservation Tillage Systems, and weed management is discussed in Chapter 9: Integrated Weed Management.

Annual Crop-Fallow Transition AEC ▲

The average fractions of winter wheat (41%), spring wheat (16%), and spring barley (4%) in the Transition AEC were very similar to the Annual Crop AEC, whereas nearly 28% of the transition acreage was in fallow and just 3% in broadleaf crops from 2007 to 2014 (Table 5-1). Crop diversity noticeably increased during this period. Total broadleaf crop acreage doubled; peas increased 65%, to more than 39,000 acres in 2014. Beginning in 2011, chickpea and canola acreage grew rapidly, to more than 13,500 and 15,000 acres, respectively, in 2014 (Figure 5-1).

Much of the Transition AEC is cropped in the 2-year WW-F sequence, shifting to an intensified 3-year rotation, typically winter wheat-spring grain–fallow (WW-SW-F or WW-SB-F) or, less commonly, winter wheat-spring broadleaf-fallow in areas with sufficient moisture (Table 5-2). The transition region has more variable moisture conditions and lower overall productivity compared to the Annual Crop AEC. Crop choice is limited by available water; winter wheat has been the most reliable crop. Soils generally have lower soil water holding capacity (1.8–2.2 in/ft) and soil organic matter (2–3%). The topography includes steep to gentle slopes that are susceptible to erosion by water or wind. Pockets of shallow soils (<40”) that do not benefit from precipitation storage during a fallow period are generally cropped annually. These areas have low annual yield potential (Douglas et al. 1999). Tilled fallow is common, especially in the drier areas, to maintain seed zone moisture and control weeds, but most growers in the Transition AEC have adopted some form of reduced tillage, or no-till (Douglas et al. 1992; Schillinger et al. 2003; Schillinger and Papendick 2009).

Both diversification and intensification strategies have potential in the Transition AEC (Table 5-3). No-till, **flex cropping**, and practices such as integrating tall cereals, harvesting with a stripper header, or undercutter tillage fallow increase the potential for intensification of traditional rotations and limit missed production opportunities. Flex cropping when conditions are favorable (good market price, low weed pressure, adequate moisture), can increase carbon sequestration and enhance soil organic matter (Lutcher et al. 2013). A few highly innovative producers have had success with 4- and 5-year crop sequences integrating no-till winter and spring cereals, spring pea, winter pea, canola, and camelina with 12–14” precipitation, and with direct seed flex cropping systems on shallow soils (2–3 feet deep) in a traditional winter wheat-fallow area with 12” average precipitation (Yorgey et al. 2016a; 2016b). Warm season crops (corn, safflower, sunflower, and proso millet) have had limited success due to high water demand, inadequate heat units, highly variable yields, and limited market access (Schillinger et al. 2003).

Grain-Fallow AEC ■

The Grain-Fallow AEC is the largest dryland production area in the inland PNW. This region is characterized by poor soil health, drought, high pest pressure, and low grain and residue productivity. Diversity is very low and opportunities to diversify or to intensify production are limited. The traditional crop sequence is the 2-year WW-F sequence with an average 50% of the acreage in fallow, annually. From 2007 to 2014, 45% of acreage was planted to winter wheat. Just over 3% of the area was in high-yielding spring wheats and barley with small areas (less than 1%) of canola, dry pea, and chickpea (Tables 5-1, 5-2, and 5-3). Both chickpea and canola acreage grew rapidly. Chickpea acreage doubled to more than 1,000 acres from 2007 to 2014, and canola acreage expanded from less than 200 acres in 2007 to around 14,000 in 2013 and 2014 (Figure 5-1). However, these values still represent a tiny fraction of the Grain-Fallow AEC.

Producers are seeking more sustainable alternatives to the intensively tilled fallow system, which exposes soil to erosion, degrades soil organic matter, and represents missed production opportunities. Moisture is generally insufficient to support profitable annual cropping, and growers rely on fallow practices to store and retain winter precipitation in the soil profile, maintain seed zone moisture to establish winter wheat, mineralize soil nitrogen (N), and stabilize yield and profitability. Blowing dust continues to be a severe environmental issue. Poorly **aggregated** soils with relatively low soil water holding capacity (1.6–2 in/ft) and low organic matter (<1.5%) are extremely susceptible to high rates of wind erosion.

Annual cropping of no-till spring grains has not proven economical to date, but there are opportunities to diversify the winter wheat phase of the rotation with winter triticale, winter peas, and winter canola, and to intensify rotations using flex cropping, depending on yield potential and commodity prices. The adoption of no-till fallow is limited by excess soil water evaporation from the seed zone compared to **conventional tillage**; inadequate seed zone moisture at optimal planting dates can delay seeding and reduce yields. Reduced-till fallow using undercutter tillage shows promise to successfully control weeds, reduce erosion potential, and retain seed zone moisture (Huggins et al. 2015; Schillinger et al. 2003; Schillinger et al. 2010; Young et al. 2015).

Integrating Diversification Strategies: Grower Considerations and Supporting Research

The following section presents considerations for integrating alternate crops, cover crops, or flex cropping, such as rotational fit, stand establishment, weed and N management, and the effect of an alternate crop on subsequent wheat yield. Potential for alternate crop adaptation to the dryland AECs, typical grain and residue yields, N requirements, and water use are compared in Appendix Tables 5-A1, 5-A2, and 5-A3.

Integrating Grain Legumes

Rotational fit

Diversifying with grain legumes has an important role in cereal production systems, providing short- and long-term benefits. Short-term benefits include (1) biological N fixation which improves soil fertility and reduces reliance on N inputs, (2) options for controlling grass weeds that are persistent in annual cereal systems, (3) reduced disease and pest pressure, (4) moderate water use conserves soil water reserves for subsequent crops, and (5) ability to flex crop or plant an opportunity crop (Chen et al. 2006; McPhee and Muehlbauer 2005). Improved soil tilth and reduced greenhouse gas emissions associated with N fertilizer production and reactive soil N are examples of long-term benefits. European studies found that arable cropping systems with legumes reduced nitrous oxide emissions and N fertilizer use 18% and 24%, respectively, compared to systems with no legumes, mitigating climate change and saving growers money (Reckling et al. 2016). Grain legumes efficiently utilize residual soil nitrates, reducing the potential for N loss by **leaching** (Mahler 2005a; Muehlbauer and Rhoades 2016) and wheat yields following pea or lentil can be 10–20% greater than in a wheat-fallow rotation (Guy and Gareau 1998; Guy and Karow 2009). ●▲

Dry peas and lentils have been produced in the inland PNW since the 1920s, primarily in the Annual Crop AEC, replacing a year of cereal or fallow. Low pea and lentil prices in the 1970s spurred interest in chickpea production, and the area is now the leading chickpea production region in the US.

Cool season peas, lentils, and chickpeas are well-adapted to the inland PNW cereal production system, yet performance and yield of spring-planted legumes can be limited by late-season drought and heat stress. Early planting can offset risk, but busy spring workloads or excessive wet and cool soil conditions can delay or even prevent spring field operations. Predicted climate change may intensify these limitations; increased late-winter and early-spring precipitation may make early-spring planting more difficult, and hotter, drier summers may increase drought and heat stress. Researchers found a strong relationship between dry pea yield and available soil moisture during the June-August period; pea yields were reduced 20% in years with below-average moisture (Abatzoglou and Eigenbrode 2016). The deeper rooting habit, drought tolerance, and lower susceptibility to high temperatures of chickpeas during flowering may be better adapted to future conditions than peas. Planting winter-hardy legumes can be useful for adapting to climate change with the advantages of increased yield and improved water use efficiency compared to spring-sown legumes or fallow; maximum crop growth of fall-seeded legumes occurs in early spring when evapotranspiration is low (Gan et al. 2015; Muehlbauer and McPhee 2007).

Successful integration of grain legumes depends on defining the best rotational fit, within each AEC, to enhance overall productivity of the cropping system. Direct seed or reduced tillage systems enhance stand establishment and help protect soils when integrating legume crops which produce less residue that decomposes more rapidly than cereals. Spring grain legumes are suited to the Annual Crop AEC where sufficient precipitation supports continuous cropping and higher productivity. In the Transition and Grain-Fallow AECs, spring legumes can be used to replant failed fall-sown crops such as winter canola, winter pea, or lentil, or planted as an opportunity or flex crop option to replace fallow. In low production areas where shallow soils have less total available water than deep soils, spring dry pea or lentils can provide an alternate crop with less water uptake and similar water use efficiency as spring wheat. In eastern Oregon studies, lentils outperformed other legumes in locations with less than 14” precipitation and have potential as an alternate crop; chickpea has potential to replace dry pea in a traditional WW-P rotation, but typically uses too much soil water to replace fallow in the WW-F rotation without reducing wheat yield (Machado et al. 2006a; 2006b). ▲■

Recent releases of high-yielding winter cultivars provide producers a viable alternative to integrate or increase legumes in their rotations and

Why Winter Pea Can Work in Conservation Systems

●▲■

1. Excellent rotation crop for winter wheat
2. Viable economic potential
    a. High yield potential
    b. Reliable market
    c. Diversified farm income
3. Planting and emergence flexibility
4. Improved winter survival
5. N fixation – low fertilizer input
6. Wide adaptation across precipitation zones
7. Low soil acidification during winter pea sequence
8. Good water use efficiency
9. Residue is easily managed

Source: Guy 2016

avoid many of the challenges associated with spring direct-seed planting. Fall-planted winter peas can be adapted across the region and provide needed diversity in the Transition and Grain-Fallow AECs (see the Why Winter Pea Can Work in Conservation Systems sidebar). Fall-sown winter cultivars offer many advantages over spring pulses: (1) 30–50% or more greater yield, (2) improved water use efficiency, (3) better weed competitiveness, (4) earlier maturity, and (5) better protection against soil erosion with over-winter surface cover and higher biomass production (Chen et al. 2006; Kephart et al. 1990; McPhee and Muehlbauer 2005).

Austrian winter peas were first produced in the PNW in the 1930s, and grown for feed and green manures. Turkish red 'Morton' winter lentils were developed specifically for use in direct seed or reduced tillage systems and released in 2004. As interest in winter legumes has grown, PNW breeding and variety trial programs have broadened efforts to develop improved winter hardiness in food quality winter peas; winter peas for forage, feed, and cover cropping; and winter lentils. Chickpea and Austrian winter feed pea studies also continue (McGee et al. 2014; McPhee and Muehlbauer 2005). As locally adapted, food quality (non-pigmented), winter-hardy pea cultivars become more available, market opportunities will expand. Recent grade standard revisions allow producers to market food quality winter peas as smooth, dry, yellow, or green peas, similar to spring types, when size is adequate (Table 5-4). Food quality winter peas have a clear seed coat and hilum, white flowers, and high palatability compared to Austrian winter peas that have pigmented seed coats, purple flowers, slightly lower palatability due to tannin content, smaller seed size and, typically, longer vines. 'Lynx' peas have improved winter hardiness to –5°F and a clear seed coat with potential for the food market.

Winter pea yields are variable with location, variety, and crop year. McGee and McPhee (2012) reported winter pea yields at four locations from 2008–2011, averaged across four varieties ('Lynx,' 'Whistler,' 'Windham,' and 'Specter') and ranging from 817 lb/acre near Wilbur, Washington to just under 3,100 lb/acre near Pullman, Washington (data not shown), and Guy (2016) reported 1,810–3,840 lb/acre grain yield of 'Windham' peas at locations in Transition and Grain-Fallow AECs (Table 5-5; Figure 5-2). These values represent yields that a grower may expect to achieve. Austrian winter pea acreage grew rapidly during the 2011–2015 period, most of which is likely located in the Annual

Table 5-4. Winter pea characteristics.

Variety	Class	Vine Type	Winter Hardiness	Height, Max (in)	Grams/ 100 Seeds	Seed Coat	Flower Color	Tannin-Free
'Lynx'	Green	Short-semi leafless	–5°F	35	15.4	Clear	White	Yes
'Windham'	Yellow	Short-semi leafless	0°F	29	14.5	Subtly Mottled	White	Yes
'Whistler'	Yellow	Short-semi leafless	+5°F	32	16.60	Mottled	White	Yes
'Specter'	Yellow	Tall-semi leafless	+5°F	40	13.5	Subtly Mottled	White	Yes
Austrian	Purple	Tall-normal	+10°F	65	12–14	Mottled	Purple	No

Sources: McGee et al. 2012; McPhee and Muehlbauer 2007.

Table 5-5. 'Windham' winter pea yield and returns in eastern Washington (2009). ▲ ■

Location	MAP[1] (in)	Acres	Yield (lb/ac)	$/lb	Gross $/ac
Ritzville ■	12	47	1,810	0.18	325
Waterville ▲	15	217	3,660	0.18	660
Sprague ▲	16	146	3,840	0.18	690

[1]Mean annual precipitation
Source: Guy 2016.

Figure 5-2. 'Windham' winter peas near Ritzville, Washington, in 2009. (Photo by Stephen Guy.)

Crop AEC (Table 5-6). Yields were similar across years; high yields in 2011 were likely a result of plentiful winter precipitation. Currently, NASS does not track yellow and green winter peas.

Small, red lentils have potential to substitute for fallow sequences in traditional WW-F rotations in the Transition AEC. Small reds have good yield potential and marketability, do not require N inputs, are adaptable to no-till systems, use less water than larger lentils, and have potential for **recrop** wheat. Early studies (1987–1988) near Davenport, Washington

(14" MAP), showed spring-planted yields over 1,200 lb/acre (data not shown). Small red spring lentils are less adapted to the Annual Crop AEC where large red or yellow lentils have higher yield potential (Veseth 1989).

High-value, food-quality peas may earn a 50% price premium over feed peas (McGee and McPhee 2012; McGee et al. 2014; McPhee and Muehlbauer 2007). However, at Wilbur, 2015 revenues for fall-planted peas for food were less than revenues for peas for cover crop seed market and for winter wheat; cover crop peas had a $7 per hundredweight premium over food market winter peas. Revenues were between $350–$400/acre for 'Windham' and 'Lynx' peas for cover, higher than for most other winter crops and spring grains (Nelson 2016; data not shown). Guy (2016) reported gross revenues for 'Windham' peas from $325 to $690/acre based on yield and location (Table 5-6).

Small, red 'Morton' winter lentils are well-adapted to the Annual AEC and flex crop conservation tillage systems. ●▲ Muehlbauer and McPhee (2007) reported that fall-planted 'Morton' lentils had 108% greater yield than spring lentils (73% more than highest yielding spring lentils). Recent 'Morton' winter lentil average yields ranged from 2,065 to 5,195 lb/acre over multiple years (2009–2014), similar to 'Windham' winter pea (2,439 to 5,642 lb/acre) in USDA-ARS variety trials (Table 5-7).

Winter peas offer advantages over spring legumes: overwinter soil cover, greater yield potential, and earlier maturation than spring-planted peas, avoiding heat and water deficits that occur later in the growing season. Winter pea yields can more than double spring pea yields (Table 5-8). While there are many advantages to integrating winter legumes in crop rotations, significant agronomic challenges need to be addressed including (1) optimal sowing dates and rates, (2) improved winter survival, (3) control of late-emerging broadleaf weeds, and (4) sensitivity to sulfonylurea (SU) herbicide carryover.

Plant establishment

Early seeding of cool season spring grain legumes enables plants to flower and set pods prior to droughty, hot conditions. These crops benefit from seeding as soon as field work can be done, typically mid-March to mid-April, once soil temperatures reach 40°F. Pea and lentil yield potential

Table 5-6. PNW dryland Austrian winter pea production for Idaho, Washington, and Oregon.

Year	AWP	
	Acres	lb/ac
2015	17,000	1,441
2014	7,638	1,604
2013	10,707	1,598
2012	6,950	1,577
2011	5,800	1,723
5-year average	9,619	1,588

Source: Todd Scholz, USA Dry Pea and Lentil Council.

Table 5-7. Average yields of 'Morton' winter lentil and 'Windham' winter pea in the Annual Crop agroecological class. ●

Year	'Morton' Lentil ●	'Windham' Pea ●
	lb/ac	
2014	2,065	2,995
2013	3,362	1,784
2012	4,248	4,231
2011	5,195	5,642
2010	—	2,435
2009	2,592	2,521

Compiled from USDA-ARS winter legume breeding variety trial reports (2012–2015).

Table 5-8. Average yield of winter and spring peas by location, in eastern Washington (2014). ● ▲

Location	Winter Pea	Spring Pea
	lb/ac	
Garfield ▲	5,135	1,589
Pullman ●	4,159	2,116
Dayton ●	3,464	1,961

Source: McGee 2016

declines when planted in May. Chickpea is somewhat less sensitive to later planting dates and has improved germination with 45°F soil temperatures for some cultivars. However, in eastern Oregon studies, chickpea yield and bean quality were favored by planting as early as possible in March, and lentil performance was affected by annual precipitation, seeding rate, date, and location; seed zone moisture and weed pressure affected stand establishment and yield potential. Low seed zone moisture at planting (after winter wheat) resulted in poor winter lentil establishment and low yield (Machado et al. 2006a; 2006b).

Seeding rates and depth vary with seed size as determined by crop and cultivar. Seeding rates are targeted to 3–4.5 plant/ft^2 for chickpea, 8–10 plant/ft^2 for pea, and 10–12 plant/ft^2 for lentil. Row spacing of 6–7” with seeding depths of 1–3” for lentil, pea, and chickpea are routinely recommended. Relatively large seed size allows for deep planting peas, lentils, and chickpeas into moisture; peas and kabuli chickpeas can be planted 4” or more to moisture when needed. Guy and Lauver (2015) conducted spring seeding rate trials at Annual Crop and Transition AEC sites using 6–11 (pea), 7–12 (lentil), and 2–8 (chickpea) seed/ft^2 and found varied results. The lowest seeding rate for pea resulted in significantly lower yields; yields at higher rates were similar. The lentil seeding rate did not affect yield, and results were consistent enough to support a 10 seed/ft^2 planting recommendation. Chickpea yields indicated that seeding rates of 3–4 seed/ft^2 yielded better than 2 seed/ft^2 and there were incremental increases in yield with increased seeding rates of 3–8 seed/ft^2. At Moro (11” MAP) and Pendleton (16” MAP), Oregon, Machado et al. (2006a) compared lentil seeding rates of 20 and 10 seed/ft^2. The higher seeding rate resulted in more plants (6–7 plant/ft^2) and higher yields than the lower seeding rate. Narrow row spacing of legumes (6”) helps control weeds while wider row spacing (12”) can achieve the same results at low precipitation sites. Corp et al. (2004) found no yield differences for 6” or 12” row spacing in chickpea.

Fall-sown, winter-hardy pulse crops are well-adapted for direct seeding into standing cereal stubble and yield more than conventionally seeded pulses. Studies from the northern Plains and the PNW show that stubble enhances early growth and winter survival, reduces erosion and evaporation, and improves soil water recharge, storage, and water use efficiency. Stubble height does not appear to affect yield, and improves harvest of legume crops

(Chen et al. 2006; Cutforth et al. 2002; Huggins and Pan 1991; Muehlbauer and Rhoades 2016; Papendick and Miller 1977).

Recent studies indicate that there is a reasonably wide planting window for fall-seeded legumes. Optimal seeding dates are similar to those for winter wheat seeding (late August through October, depending on location). Timing should allow for adequate fall growth to support winter survival and early spring vigor; plants should reach the 2–3” tall rosette stage before winter dormancy (Guy pers. comm.; McPhee and Muehlbauer 2005). Chen et al. (2006) documented that winter pea and lentil cultivars, seeded into stubble, have greater yield potential than spring cultivars when planted at both ‘early’ and ‘late’ seeding dates in central Montana, although the earlier seeding can increase winter survivability and yield.

Establishing winter peas is easier than small-seeded oilseeds, which may be helpful if future hotter, drier, summers create more challenging conditions. Larger seed size allows for deeper planting in order to access seed zone moisture; winter pea cultivars such as ‘Windham’ can be deep-planted into moisture and emerge through 6” or more of soil (Guy 2016; Nelson 2016). Also, an extended planting window may allow fall-seeded legumes to benefit from early fall precipitation. Seeding rates vary from 30 lb seed/acre for winter lentil and up to 120 lb seed/acre for winter pea.

Weed management

Incorporating broadleaf crop sequences into cereal production systems provides opportunities for chemical control of grassy weeds such as downy brome, jointed goatgrass, wild oats, and feral cereal rye that persist in annual crop cereal systems and reduce yields in subsequent wheat crops. For more information on weeds and alternative rotations for management, see Chapter 9: Integrated Weed Management.

The PNW Weed Management Handbook and other sources provide guidelines for chemical weed control in grain legumes. Post-emergent herbicides are labeled for use in dry pea, chickpea, and lentil to control annual grasses. However, Italian ryegrass herbicide resistance has developed to the Group 1 post-emergent herbicides, which are the only post-emergent grass weed options registered for use in lentil, chickpea, and winter pea; control is useful only against non-resistant biotypes.

In-crop weed control is one of the most significant production challenges for grain legumes, particularly spring-sown crops. Few broadleaf herbicides are registered for use in lentil and chickpea. Fields with high broadleaf-weed seed infestation are not suitable for lentil and chickpea production. Pre-emergent herbicides have limited effectiveness, and there are no post-emergent chemical options for control of annual broadleaf weeds registered for use in chickpeas; metribuzin is registered for use in lentils, along with imazamox (only on Clearfield lentils). Additional materials and modes of action are available for dry pea, for both grass and broadleaf weeds.

Producers should avoid planting legumes in fields with heavy weed pressure; weeds can reduce grain legume yields 67% and complicate harvest operations (Campbell 2016). Short-statured lentils and chickpeas have slow initial growth and open canopy habits, and lack competitiveness against both early- and late-emerging weeds. Pea stands establish and close the canopy more quickly than lentils and chickpea; leafy pea cultivars are more competitive than semi-leafless types if they do not have a strong branching habit. When peas lodge, weeds can grow above the canopy. A wider number of herbicides are registered for use in peas compared to lentil and chickpea.

Cultural practices are not highly effective for weed control in pulses. Shallow seeding and earlier emergence can give seedlings a head start on weeds that emerge earlier than deep-planted pulses; however, this practice increases the potential for herbicide damage. Increased seeding rates have been shown to be only slightly beneficial for controlling weeds. Delayed seeding, to allow for mechanical or chemical control of early weeds, reduces yield potential resulting from increased temperatures and drought before maturity. Weedy stands may require application of a pre-harvest dessicant, increasing production costs. Inadequate weed control in grain legume sequences can impact subsequent crops from higher weed seed populations (Campbell 2016).

Nitrogen management

Grain legumes can improve soil N status, reduce N leaching, and improve the carbon footprint of cropping systems by replacing N fertilizer inputs; production of commercial N fertilizer accounts for a third of the total energy input to crop production. Pulse crops are able to utilize residual soil N, supplement their N needs by symbiotic fixation of atmospheric N, and leave surplus available soil N for use by a subsequent crop such as winter wheat (Bezdicek et al. 1989; Mahler 2005a; 2005b; Muehlbauer and Rhoades 2016; NRCS 2014). Whereas both the fallow system and legumes improve the soil N balance, fallowing releases N from the mineralization of soil organic matter and depletes the organic matter in the process. Canadian dryland studies showed that the benefits of summer fallow (stored precipitation and mineralized N) could be successfully replaced by diversifying with grain legumes. Also, an L-SW rotation had a 127% lower per-area carbon footprint than continuous SW and was 153% lower than F-SW-SW rotations; similarly, the L-SW rotation had the lowest per-grain carbon footprint (Gan et al. 2014; 2015).

Legume N management

Applying N fertilizer to legume crops is generally not economical (Mahler 2015; Muehlbauer et al. 1981). Peas, lentils, and chickpeas planted in soils with less than 20 lb N/acre may benefit from low rates (20–30 lb N/acre) to sustain seedlings until nodulation occurs and biological N fixation begins. High soil N may reduce biological N fixation, and fall-planted legumes with elevated N content and excess vegetative growth are more prone to winter injury (Corp et al. 2004; Murray et al. 1987).

Peas and lentils benefit from inoculation with a specific *Rhizobium* strain when they are planted in new fields or where they have not been grown in the past 20 years. *Rhizobium* specific to chickpea are not common in PNW fields and may not persist between crops; seeds should be inoculated where chickpea has not been grown in the past two years (Mahler 2005a; 2005b; 2015; Muehlbauer et al. 1981).

N management for crops following grain legumes

Nitrogen from legume residues increases the soil N balance and should be credited against total N requirements for subsequent crops. The N credits to wheat following grain legumes are shown in Table 5-9 and are based on legume grain production. Estimated N credits from lentils producing 1,000 lb/acre seed and dry peas producing 2,500 lb/acre seed are 10 and 20 lb N/acre, respectively. Using a rough conversion factor of grain yield × 0.008 helps estimate potential N credit from chickpea, winter lentil, or pea.

Mahler and Guy (2005) illustrate a slightly different method to estimate credits to N requirements of spring canola following legumes (Table 5-10). At planting, an estimated 60% of the previous legume residue will have decomposed and should be accounted for in a pre-plant soil test as plant-available N. To account for N from the fraction of the residue that has not yet broken down, 1 ton of residue is equivalent to 6 lb N/acre credit. See Chapter 6: Soil Fertility Management for more information on N management.

Rotation effect

Peas, lentil, and chickpeas are short season, shallow-rooted crops and generally use 15–35% less water than cereals or oilseeds, leaving more water in the profile for subsequent crops. Dry pea has the highest productivity (grain and residue) and water use efficiency compared to

Table 5-9. Estimated nitrogen (N) credit to wheat from preceding grain legume.

Crop	Grain yield lb/ac	N credit lb N/ac
Lentil[1]	>1,000	10
Chickpea	>2,000	15
Dry pea[1]	>2,500	20
Winter lentil	>2,500	20
Winter pea	>3,750	30

[1]Koenig 2005.

Table 5-10. Estimated nitrogen (N) credit to spring canola from legume residue breakdown.

Tons Residue	Grain yield lb/ac[1]	N credit lb N/ac
0.5	500	3
1	1,000	6
2	2,000	12
3	3,000	18
4	4,000	24

Source: Mahler and Guy 2005.
[1]residue-to-grain ratio used = 1 ton residue per 1,000/lb pea (or lentil) seed.

lentil and chickpea. In general, water use is lowest for lentil and highest for chickpea (Table 5-A3). Peas and lentils extract most of their water from the upper 2 feet of the soil profile; chickpea has a deeper effective rooting depth of 3–4 feet and a longer growing season, leading to the higher water use (Corp et al. 2004; Gan et al. 2009; Gan et al. 2015).

Recent studies have aimed to define the rotation effect of integrating a winter pea sequence. Results have been mixed. Ritzville, Washington (12" MAP), studies at the Jirava farm (2010–2015) showed a benefit to spring wheat yield after 'Windham' winter pea in a 3-year rotation (WP-SW-F) compared to spring wheat yield after winter wheat (WW-SW-F). Winter pea and winter wheat yields averaged 2,094 lb/acre and 72 bu/acre, respectively, over 4 years. Subsequent spring wheat yields averaged 30 bu/acre following winter pea compared to 28 bu/acre after winter wheat. Winter pea used significantly less water than winter wheat. Likewise, available soil water levels for planting spring wheat were higher after winter pea than after winter wheat, even though winter precipitation storage efficiency was higher following winter wheat, a result of drier soil and greater residue production (Schillinger et al. 2016). ▲ ■

At a traditional WW-F site in Montana (14" MAP), Chen et al. (2012) found that winter wheat yield and N recovery in grain were higher in a WP(hay)-WW sequence compared to SW-WW and similar to WW-F, and benefitted from income for hay. Smiley and Machado (2009) reported that replacing summer fallow with winter pea reduced subsequent winter wheat yields at Moro, but had little effect on winter wheat yields at Pendleton (2000–2005). However, nematode populations were greater under winter pea than spring cereals.

Integrating Canola

Rotational fit

Interest in regional energy crops and rotational diversification spurred feasibility research on canola for food, feed, and fuel production beginning in the 1970s; however, commercial adaptation of canola in the inland PNW has lagged behind other dryland production regions. Successful adaptation depends on defining wheat-canola sequences, specific to each AEC, that improve weed control and stand establishment under hot, dry conditions during optimal planting date windows, maximize winter survival, and enhance soil water and N recharge and uptake throughout the growing season (Long et al. 2016; Pan et al. 2016).

Spring canola is the better-adapted option for annual crop systems and can replace either spring legumes or cereals. Pan et al. (2016) found that spring canola yields are correlated with total available water and had water use efficiency of 182 lb grain yield per inch of water used. Winter canola is less suited to the Annual Crop AEC; soil moisture and growing degree days after cereal harvest are often insufficient to establish and grow winter canola to an adequate size (3–4 leaf rosette stage) before freezing winter conditions. Winter oilseeds have a role in annual crop systems when seeded after fallow or in ‘delayed planting’ in years with unfavorable spring seeding conditions, when soil water is sufficient for fall planting. ● ▲

Both winter and spring canola can be adapted to the Transition AEC with positive benefits, and grain-fallow producers are integrating winter canola to improve pest management strategies, diversify markets, and increase sustainability. Spring canola is less commonly grown in the Grain-Fallow AEC because yields are only 50–60% those of winter canola, limiting profitability (Hulbert et al. 2012; Karow 2014; Long 2016; Pakish et al. 2015; Pan et al. 2016). According to Young et al. (2012), spring canola could fit into grain-fallow systems “as a replant crop in instances of winterkilled, fall-planted canola, or as an opportunity crop during cycles of above-normal precipitation.” As an opportunity crop, or flex crop, growers might include spring canola when prices are strong and moisture conditions are favorable (based on historical in-season precipitation data), or when available soil moisture is sufficient to a 48” rooting depth. New information from research on canola production in the Grain-Fallow AEC is becoming available which will give growers tools to reduce risk and support adoption. ▲ ■

The greatest agronomic challenges to adoption of oilseeds across the region include:

- Inconsistent stand establishment and yields
- Environmental limitations during optimal planting windows
- Winter survival of winter crop types

- Sensitivity to imidazolinone (IMI) and sulfonylurea (SU) herbicide carryover

Canola can be direct seeded into stubble, or into reduced-till or conventionally tilled soils. Cold, wet conditions may delay spring planting operations past optimal yield windows or early plantings may suffer frost damage. Fall operations are hindered by lack of seed zone moisture and high ambient and soil temperatures. Direct seeding may slow seedling development but conserves moisture for the crop and reduces erosion; increased seeding rates can enhance stand establishment.

Notable agronomic benefits growers have experienced include:

- 10–30% yield benefits to subsequent wheat crops
- Integrating herbicide-resistant canola has improved grassy weed control
- Improved **soil structure** and **infiltration**, and reduced runoff

Several eastern Washington growers have shared their experiences with integrating canola and other oilseeds in a series of case studies (Sowers et al. 2011; 2012).

Rotation effect

Improved winter wheat yields following grain legumes are well-documented. Guy and Karow (2009) compared winter wheat yields following several rotational crops, expressed as a percentage of yield following pea (100%). Relative winter wheat yields after cereals were 74–86% of wheat after pea at Moscow and Genesee, Idaho (Annual Crop AEC); yields after brassica crops were 85–99% of yields after pea, indicating similarly strong potential rotation benefits (Figure 5-3). ●▲ Calculations derived from recent biofuel cropping systems studies (2011–2013) showed similar results based on three years of yields of winter wheat following spring crops: relative wheat yields were highest following pea (100%) and lentil (99%); wheat yields after spring canola and camelina were 90% of yield after pea. Earlier studies showed winter wheat grown after five different broadleaf crops averaged 29% greater yield than winter wheat following winter wheat, while the rotation benefit of winter wheat after spring cereals averaged just 9% (Guy 2014; data not shown).

Wheat yields following canola are generally expected to be greater than yields after wheat. However, yield impacts are not always positive, or clearly understood. Select north-central Washington growers have achieved 30% yield increases of winter wheat in rotation with canola (Sowers et al. 2012), and on-farm studies near Ritzville, from 2006 to 2009, showed winter wheat following canola had 39% greater yields than winter wheat following wheat (Esser and Hennings 2012). ▲ ■ In contrast, rotation studies near Reardan, Washington (14” MAP), showed spring wheat yields following winter wheat (58 bu/acre) were similar to spring wheat yields following winter canola (49 bu/acre) over 5 years (2009–2010; 2012–2014). Soil water use by winter wheat and canola were similar, as was soil water content when spring wheat was seeded, whereas suppressed mycorrhizal fungi populations under spring wheat after canola may have limited the potential rotation benefit (Schillinger et al. 2013; 2014a; Hansen et al. 2016).

Recent studies at the Washington State University Wilke Research and Extension Farm (Davenport), showed variable spring wheat yield

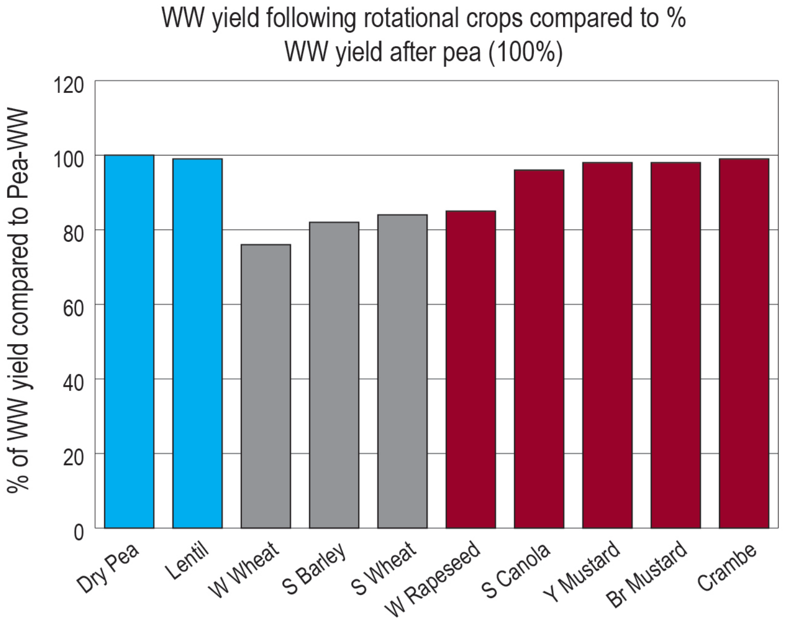

Figure 5-3. Winter wheat (WW) yields following rotational crops expressed as a percentage of yield following pea (5-year average at Genesee and Moscow, Idaho). Legumes are in blue, cereals in gray, and oilseed crops in red. (Adapted from Guy and Karow 2009.) ●

responses (2013–2015): two of three years showed yield benefits (8% and 16%) for spring wheat following canola compared to winter wheat. However, yields of spring wheat following canola were 6% less than following winter wheat in 2015 (Esser and Appel 2016). Yield benefits to wheat after canola have not yet been documented from long-term research sites in the PNW (Long et al. 2016). Integrating canola offers other positive rotation effects; canola stubble can trap snow, reduce runoff, and improve soil water recharge. Additional soil moisture can increase potential biomass production, soil organic matter, and water-holding capacity, leading to more opportunities for intensification.

Spring canola establishment

Canola emergence is impacted by wet soils, soil crusting, and sensitivity to herbicide carryover, such as Pursuit. For optimal germination and yield, spring seeding should be done as soon as soil temperatures reach 49°F and fields are suitable for machinery. Seeding spring canola into heavy winter wheat residue is challenging; establishment is typically just 50–60% of the seeding rate. Cold soil temperatures slow seedling growth in early plantings, while later seeding reduces yield potential. Typical canola seeding rates are 4.5–6 lb/acre for the Annual Crop AEC, targeted to establish a stand count of 4–10 plant/ft^2 at harvest. Canola seed size and weight are highly variable; seeding rates should be adjusted based on seed lot information. Direct seeding or broadcast methods benefit from higher rates than for conventionally tilled fields (Brown et al. 2009). Spring canola stands are more consistent when planted before seed zone moisture declines and temperatures warm; later plantings result in increased heat and drought stress during flowering and grain fill (Brown et al. 2009; Gan et al. 2004; Pan et al. 2016). Spring canola direct-seeded into heavy wheat residue over 9 years showed an inverse relationship between seeding date and grain yield (Huggins and Painter 2011). A 2-year study showed yields were not affected by row spacing (10” or 20”) with a 5 lb/acre seeding rate. Advantages of wider row spacing include lower machine and fuel costs and less drill plugging (Pan et al. 2016; Young et al. 2012). Karow (2014) recommends 5–8 lb/acre seeding rates and 12–16” row spacing for spring canola in eastern Oregon; narrower row spacing helps control weeds. ●▲

Winter canola establishment

The greatest challenge growers face with winter canola is consistent stand establishment. Insufficient seed zone moisture and excessive temperatures during germination can lead to inconsistent stands or even crop failure; poor establishment increases risk of winterkill. Conditions are most favorable with adequate seed zone moisture within an inch of the soil surface and cool air temperatures (<84°F) for a week after planting. Small seeded canola (0.2–0.6 g/100 seed) cannot be planted deeply into moisture like wheat or peas. Canola emerges best when planted just 0.8–1.2" below the soil surface, but can emerge from twice that depth when needed to access moisture (Karow 2014; Pan et al. 2016). In the Grain-Fallow AEC, soil moisture is often 4–6" below the surface in summer fallow in August. Planting with deep furrow drills can be successful when seeds need to emerge just to the bottom of furrow. Young et al. (2014a) found 22% improved plant density, more uniform distribution, better growth, and improved weed suppression growth when canola was planted with deep furrow drills modified with 10–15" shovels to move hot, dry soil away from the seed zone. ▲ ■

Guidelines for optimal winter canola planting dates and rates have been lacking for the low precipitation grain-fallow systems. Information from recent studies helps growers reduce risk and achieve successful stands and yields. Mid-August to early-September planting dates are optimal for achieving adequate growth for winter survival (rosette stage) and yield potential (Brown et al. 2009; Karow 2014); Young et al. (2014a) found early August to about August 25th to be the optimal planting window with soil moisture less than 4" below the soil. Late seeding of winter canola, to take advantage of fall rains, significantly reduces both survival and yield. September plantings showed reduced yields of nearly 40% compared with an August planting (Pan et al. 2016).

Integration of biennial, dual-purpose canola cultivars, provides growers the intensification option to produce both forage and grain from a single planting (Kirkegaard et al. 2008b; Neely 2010). This allows earlier seeding of winter canola, enabling better seed germination and plant growth while the soil moisture during fallow is still close to the soil surface, and improves yield consistency (Karow 2014). Several growers in the Transition AEC have had success with early-July seeding. The first season's forage can

Figure 5-4. Cattle grazing a biennial, dual purpose canola stand near Ritzville, WA. (Photo by Karen Sowers.)

be grazed (Figure 5-4) or used to produce silage (Kincaid et al. 2011). Recovering plants are capable of overwintering, and then proceed into stem elongation and reproductive phases in producing competitive grain yields in the following season. Continued development of varieties with improved tolerance to cold temperatures and open winters will reduce production risks for this region.

Canola seed size is highly variable; having accurate seed lot weights helps set appropriate seed rates to achieve target plant populations. Brown et al. (2009) guidelines recommend that growers determine a seed rate targeted to 10–16 seedling/ft^2 at establishment to give 5–10 plant/ft^2 at maturity. Karow (2014) recommends a seeding rate of 4–7 lb/acre for eastern Oregon; Young et al. (2014a) found 4 lb/acre to be optimal for seeding in grain-fallow locations with 10” MAP. A Ritzville area grower reduces risk by increasing his seed rate to 7 lb/acre when the soil moisture line is lower than 4” below the surface. Canola yields generally decrease significantly when the mature stand population drops below 4 plant/ft^2. However, canola growth is indeterminate, and less dense stands can compensate in growth and yields; stands do not need to be uniform to achieve economic yields. Brown et al. (2009) reported that canola's compensatory growth habit makes it possible for winter canola stands with just 1–2 plant/ft^2 in spring to produce 70–80% of yields achieved with the higher density. Similarly, Young et al. (2014a) found that spring stands with populations of 2–4 plant/ft^2 achieved excellent yields (>1,500 lb/acre) in the Grain-Fallow AEC.

In recent planting rate and date studies at Okanogan and Bridgeport, Washington (10–10.5" MAP), Young (2012; 2014a) found optimum yields with a 4 lb/acre rate; trials had 56–83% winter survival rates, resulting in a spring stand of 2–4 plant/ft^2. For seeding spring canola following a failed winter crop, results were better with drilled seed; broadcast spring canola was more vulnerable to frost damage and yielded just 30–67% compared to drilled canola.

Winter canola is less suited to the Annual Crop AEC; moisture reserves are too low following harvest of a previous crop to plant canola in mid-August. Dry conditions extend into October and delayed seeding allows seedling growth to only a 2–3 leaf stage prior to winter conditions, leaving seedlings more vulnerable to winterkill. Canola is less winter hardy than wheat because of canola's 'epigeal' type emergence, where cotyledons and the shoot growing point emerge above the soil surface, increasing the plant's exposure and sensitivity to harsh conditions. In contrast, cereals exhibit 'hypogeal emergence,' where the shoot growing point is below-ground and protected from severe cold and other environmental stressors (Karow 2014; Klepper et al. 1984; Koenig et al 2011; Long et al. 2016; Pan et al. 2016).

Winter canola establishment considerations:

- Depth to moisture
- Soil and air temperature
- Seed rate, date, and N effect on winter survival

Weed management

Integrated weed management practices are critical to successful weed control in cereal-based cropping systems, reducing reliance on in-crop herbicides and preventing herbicide resistance. Using diverse crop sequences, reduced tillage or chemical fallow, competitive crop varieties, and seeding practices to establish optimal stands help reduce weed pressure. Well-established canola stands maximize competitiveness; canola seedlings grow and close canopy rapidly, competing well with annual weeds, while late plantings or poor stands are less competitive. (Brown et al. 2009; Karow 2014; Long 2016).

Herbicide-resistant spring canola varieties provide opportunities for better control of the grassy weeds that persist in cereal-dominated annual crop systems, such as downy brome, jointed goatgrass, feral rye, and Italian ryegrass (Brown et al. 2009; Young et al. 2016b). Replacing spring legumes with glyphosate-resistant spring canola in rotation with winter and spring cereals, over several years, was effective in reducing Italian ryegrass in studies near Pullman (Huggins and Painter 2011), and also improved control of broadleaf weeds, including mayweed chamomile and common lambsquarters that are difficult to control in legume sequences. Spring canola cultivars are available with resistance to glyphosate, glufosinate, or imazamox; volunteer herbicide-resistant canola may need to be controlled during fallow or subsequent crop sequences. ● ▲

Wilke Farm studies at Davenport, found that integrating herbicide-resistant spring canola in a 4-year rotation improved feral cereal rye control and improved economic returns resulting from improved canola and wheat yields (Hulbert et al. 2013); canola yields and wheat yields following canola benefitted from the improved weed control. ▲ ■

Similarly, growers in the Grain-Fallow AEC may choose to grow winter canola to improve grass weed control. Downy brome, Italian ryegrass, and jointed goatgrass persist in winter wheat along with feral rye. Typical weed control options include mechanical rod weeding in conventional or reduced tillage systems, or chemical fallow where direct seeding is utilized to reduce wind erosion (Pan et al. 2016; Young and Thorne 2004). Recent research in north-central Washington found that spring and split applications of quizalofop and glyphosate in canola controlled 90% of feral rye, eliminated seed production, and increased canola yield more than 40% (Young et al. 2016b). Use of glyphosate-resistant winter canola, plus glyphosate application, can provide additional opportunities to control feral rye. Adopting herbicide-resistant cultivars also allows for easier chemical rotation management, circumventing plant-back restrictions for IMI and SU herbicides.

Nitrogen management

Canola nutrient requirements, timing, and placement vary from traditional wheat fertilization programs. Karow (2014), Koenig et al. (2011), Mahler and Guy (2005), Pan et al. (2016), Wysocki et al. (2007), and others describe several important N management factors to consider:

- Canola N, phosphorus (P), sulfur (S), and potassium (K) uptake per unit yield can be 50–100% greater than soft white and hard red wheat uptake indicating that higher levels of available N are required for regional canola production compared with wheat nutrient management.
- The percentage of N, P, and K removed in canola grain is lower than that removed in wheat; nutrients left in oilseed residues contribute to subsequent crop sequences.
- Canola's strong taproot and extensive root hairs enhance utilization of soil N to its full rooting depth, reducing reliance on applied N.
- Fertilizer N = (yield goal × base N recommendation of 6–8 lb N/100 lb seed yield) – soil N credits.
- Fertilizer application at or near planting date, placed to the side of the seed row, will improve germination and stand establishment, enhance early growth, improve **nitrogen use efficiency**, and limit root injury from ammonia toxicity.
- High N going into winter reduces survival rates.
- Hybrid cultivars with higher yield potential may need higher levels of N for optimal yield compared to open-pollinated varieties.

Canola response to N is influenced by climate, available soil N, cultivar, water availability and management practices; further research is needed to determine optimal timing and rates for the different AECs. Spring canola yield responds well to applied N when residual soil N levels are low, and shows minimal fertilizer N response when soil N supply is high and yield potential is low (Maaz et al. 2016; Pan et al. 2016).

Unit nitrogen requirements (UNRs) for wheat are estimated at 4.5 to 6 lb N/100 lb grain, for soft and hard wheat, respectively. Recommended UNRs for canola range from 6 to 10.7 lb N/100 lb seed for dryland production (Karow 2014; Koenig 2011). Observations over 6 years in the Annual Crop AEC showed variable UNRs of 7–13 lb N/100 lb grain for spring canola, affected by water availability. Requirements at the Wilke Farm site in the Transition AEC ranged from 9–17 lb N/100 lb grain. High UNR values resulted from lower yields and nitrogen use efficiency in this region and more complete accounting of root zone residual N and crediting of soil N mineralization contributions to the total N supply (Pan et al. 2016). Spring canola yielding up to 916 lb/acre had an average optimal N rate of 20 lb N/acre; zero N was required following fallow, compared to 5–58 lb N/acre following wheat despite lower available soil water and canola yield potential. The modest optimal N rates were influenced by high residual soil N carryover and mineralization.

Optimal fertilizer rate, timing, and placement need to be defined to maximize winter canola yield and winter hardiness. Winter canola N requirements are based on two growth phases: (1) fall growth from planting to winter dieback and dormancy, and (2) spring growth through maturity (Long et al. 2016; Pan et al. 2016). High N status of vegetative winter oilseeds decreases cold hardiness and survivability, supporting use of conservative N rates at winter canola planting, allowing winter canola to use up residual soil N during early establishment. Karow (2014) recommends that if fall N is needed for winter canola, apply 30 to 50 lb N/acre prior to planting and apply the remainder in the spring.

Integrating Other Oilseeds

Camelina

Camelina requires few cultural inputs, is more drought and stress tolerant than canola, and performs well in fields with marginal productivity, thus has the potential to help mitigate climate change and improve sustainability of dryland cereal production systems. More commonly grown as a summer annual, camelina is also adapted as a winter annual with hardiness similar to winter wheat. Camelina's short season (85–100 days) could offer more resilience to hotter, drier summers (Ehrensing and Guy 2008; Hulbert et al. 2012).

Similar to canola, camelina establishment is challenging. Small, variable-sized seeds require shallow planting (0.25") for successful emergence; seeds may have difficulty emerging if soil crusting occurs after rain showers. Seedlings have good frost tolerance. Camelina is highly sensitive to IMI and SU herbicides and has similar plant-back restrictions as canola. Efforts are ongoing to develop herbicide-resistant camelina varieties (Hulbert et al. 2012).

Planting date studies have shown highest yields with late-winter planting (February 15-March 1) at Lind, Washington and Pendleton, Oregon, compared to late-fall and mid-winter plantings when inadequate precipitation and control of fall-emerging weeds likely reduced stands. Establishment was similar with direct seed or broadcast, into standing stubble, with seed rates of 3–5 lb/acre; broadcast seeding required less time and expense. Late-planted camelina had greater Russian thistle populations at Lind (Hulbert et al. 2012; Schillinger et al. 2014b).

No broadleaf herbicides have been registered for weed control in camelina; dense, early planting in clean fields reduces weeds and increases competitiveness. Camelina's short season allows for harvest prior to seed set of many weeds.

Researchers are evaluating the potential for a 3-year WW-Camelina-F rotation to replace traditional 2-year WW-F rotations; good yields have been achieved by replacing fallow with camelina following winter wheat. Yield potential is dependent on annual precipitation. The taproot of camelina can efficiently extract subsoil water and N; UNRs are 5–6 lb N/100 lb seed. Expected yields run 60–70 lb seed per inch of precipitation in the PNW. Studies showed a yield range of 1,610 to 3,070 lb/acre in the annual crop region (Moscow-Pullman), 1,549–2,000 lb/acre at transition sites (Lacrosse, Washington and Pendleton), and lower, inconsistent yields of 115–1,030 lb/acre at Lind (Hulbert et al. 2012). Schillinger et al. (2014b) found similar water use efficiency among camelina trials across dryland areas (65 lb seed per acre inch water used) indicating that camelina yield can be predicted by annual precipitation. Camelina produces relatively low amounts of residue compared to cereals, a major disincentive to adopting camelina in the Grain-Fallow AEC. Sharratt and Schillinger (2014; 2016) found 57–212% increased wind erosion potential in summer fallow following camelina and safflower, compared to fallow after winter wheat, due to differences in crop residue characteristics. To protect against increased erosion, potential growers should either replace fallow with a spring crop or exclusively use no-till fallow practices.

Yellow mustard

Yellow mustard has good agronomic and economic feasibility in the dryland PNW, performs well in no-till systems, and requires few chemical inputs. Well-adapted to hot, dry conditions, yellow mustard can provide an adaptive strategy for predicted climate change, although the crop is sensitive at flowering. Mustard has relatively high water use, and wheat and mustard prices determine economic feasibility. Grain yields are similar to spring canola in the higher precipitation areas (2,000–2,500 lb/acre) and out-yields spring canola by 55% in regions with less than 12” annual precipitation. Predicted grain yield is 95 lb grain per inch annual precipitation, but will vary by cultivar and practices (J. Brown et al. 2005). Growers have greater flexibility with planting dates compared to other spring crops, and planting can be delayed for better weed control. Yellow mustard establishes quickly, can close canopy in 30 days, and is highly competitive with weeds compared to canola and safflower; some growers have had success using no herbicides. Growers should avoid planting mustard in fields with potential for catchweed bedstraw infestation that can impact seed quality and price. Crops generally mature in 80–85 days. Planting depth (0.5–1”) and spacing (6–8”) is similar to other oilseeds; 12” row spacing can be used in direct seed conditions. Recommended seeding rates are 7–8 lb/acre for conventional tillage and 8–9 lb/acre for direct seeding. Seeds can be planted after soil temperature reaches 40°F, but mustard is highly susceptible to frost damage. In eastern Oregon, planting may begin in mid-March; mid-April to early May is more suitable in the higher precipitation areas. Estimated required N (lb N/100 lb seed) range from 12.8 in high precipitation areas to 8 in low precipitation areas. Similar to other oilseeds, mustard is highly sensitive to carryover of imazamox herbicides (J. Brown et al. 2005; Wysocki and Corp 2002).

University of Idaho and Oregon State University Columbia Basin Agricultural Research Center (CBARC) variety yield trials between 2007 and 2015 showed average yields of just under 2,000 lb/acre (Moscow), 1,170 lb/acre (Davenport), 800 lb/acre (Pendleton), and 1,056 lb/acre

(Moro). Variety yield data can be found at ***http://www.cals.uidaho.edu/brassica/growers.asp***.

The rotation effect of yellow mustard on subsequent wheat crops has been variable. Guy and Karow (2009) found improved yields of wheat following yellow mustard compared to following cereal crops, while a grower near Ione, Oregon, found poor wheat yields following spring mustard, attributed to a notable increase of root-lesion nematodes following mustard (Yorgey et al. 2016b).

Safflower

Both spring and fall-seeded **facultative** safflower cultivars have potential in no-till dryland cropping systems. Low residue production increases risk of erosion; safflower should not be followed by fallow (Sharrat and Schillinger 2016). Safflower is relatively drought- and heat-tolerant due to its long taproot; however, it also has higher water use and lower water-use efficiency than wheat or other alternative crops in the region, which can reduce yield of succeeding crops. General seeding recommendations include an optimal planting window in April and May, seed depth of 1–1.5", and a seed rate target of 3 plant/ft^2. Soil crusting can hinder emergence. Safflower lacks competitiveness with weeds due to slow emergence and initial rosette growth; no broadleaf herbicides have been registered for weed control in safflower (Armah-Agyeman et al. 2002; Petrie et al. 2010).

Preliminary evaluations at Moro and Pendleton showed spring safflower grain yields ranging from 400 to 1,400 lb/acre; fall-sown, winter-hardy facultative safflower with earlier flowering and maturity showed increased yields up to 1,900 lb/acre compared to spring safflower. Yields in higher precipitation areas ranged from 2,575 to 3,135 lb/acre (Petrie et al. 2010). Safflower yields ranged from 125–1,130 lb/acre in Ritzville trials with an average 483 lb/acre over 6 years (2010–2015). ▲ ■

Relatively high water use by safflower depletes soil moisture at higher rates than other crops in rotation and can carry over through a year of fallow, reducing subsequent wheat yields. At Ritzville, wheat yield was lower in a WW-SAF-UTF sequence compared to WW-SW-UTF and WW-UTF over 4 years, but was significantly lower in only one year

(2012), indicating that wheat may benefit from some rotation effect that partially offsets lower soil water availability (Schillinger et al. 2016).

Integrating Alternate Spring Cereals for Reduced- and No-Till Late Planting

From 2007 to 2014, 20–22% of the Transition and Annual Crop AECs was planted to spring wheat and spring barley compared to 3% of the Grain-Fallow AEC (Table 5-1). Spring grains typically follow winter wheat in 3- or 4-year cropping sequences where moisture permits. Spring plantings broaden opportunities for control of winter annual grass weeds, and adequate seed zone moisture helps stands establish. However, wet spring conditions can delay or prevent planting, especially in the Annual Crop AEC.

Replacing or supplementing summer fallow with spring grains can enhance soil quality; no-till annual spring cropping could reduce susceptibility to wind erosion an estimated 95% in grain-fallow systems (Thorne et al. 2003). Annual cropping reduces the time soil is left bare between crops and increases crop residue and surface roughness, providing year-round protection from erosion. However, spring wheat yields are typically just 50–70% of winter wheat yields, and soil moisture deficits during flowering or grain fill can further reduce profitability. Annual cropping systems have had greater income risk and resulted in lower annual net returns than WW-F (Juergens et al. 2004; Schillinger and Young 2004; Young et al. 2015). Cropping sequences that improve water and nitrogen use efficiency and reduce erosion can help mitigate effects of climate change and past soil degradation.

Conventional and reduced tillage WW-F remains the most profitable crop sequence in the Grain-Fallow AEC. As an alternative to annual spring cropping, improved winter wheat harvest (e.g., stripper header), fallow (e.g., undercutter tillage), and flex cropping practices can improve residue cover and soil health, increasing potential for rotational diversification and intensification in the future. ▲ ■

Hard red spring wheat

Low prices for soft white wheat and favorable hard red wheat prices are incentives for growers to increase hard red spring wheat acreage. Whereas yields are typically lower and more variable than for soft white spring wheat, differences may be offset by potential price premiums earned for high percentage protein. However, the higher UNRs of 3–3.7 lb N/bu grain to achieve 14% protein can impact profitability and reduce nitrogen use efficiency, particularly in areas with high yield potential. Optimal N rates are dependent on yield potential, fertilizer costs and premium or discount price values related to grain protein concentration (Baker et al. 2004; B. Brown et al. 2005). More information on N management is described in Chapter 6: Soil Fertility Management.

Hard red spring wheat is well-adapted to dry areas with shallow soils, low yield potential and lower N requirements. Annual cropping with hard red spring wheat to replace WW-F can help reduce erosion, but has not been profitable in the short-term. Young et al. (2015) evaluated annual no-till hard red spring wheat cropping in a 6-year (1996–2001) study in the WW-F region near Ralston, Washington (11.5" MAP). Results showed that continuous HRSW, HRSW-SB, and SWSW-ChF no-till crop systems reduced wind erosion but were generally not profitable. This study also provided the first evaluation of a no-till SWSW-ChF system in the region, which benefitted from an 18-month window for control of winter annual grasses and cereal rye. Yields were generally greater than for continuous spring cereal sequences, but less than in a reduced-till WW-F system.

Similarly, annual no-till cropping has not been economically competitive in the Horse Heaven Hills (6" MAP) where growers are seeking alternatives to the WW-F system. Continuous HRSW had a 6-year average annual yield of 473 lb/acre compared to 1,062 lb/acre winter wheat, every other year. No differences in precipitation storage efficiency were found, and straw production was similar for both crop sequences (Schillinger and Young 2004). ▲ ■

White spring wheat

Schillinger et al. (2007) evaluated annual no-till cropping as an alternative to WW-F in an 8-year study near Ritzville. SWSW-SB, HWSW-SB, and continuous SWSW and HWSW sequences generally had lower average profitability and higher economic variability compared to values reported by traditional WW-F producers. Continuous SWSW had 4-year average yields similar to spring barley and out-yielded hard white spring wheat. ▲ ■

Spring barley

Historically, spring barley was a preferred alternate crop in the inland PNW. However, Washington production declined significantly from 500,000 acres in 2000 to just 110,000 in 2015. NASS (2015) cropland data showed an average 169,000 barley acres across the dryland AECs during the 2007 to 2014 period, accounting for 5% of the cropped ground in the Annual and Transition AECs, and less than 1% in the Grain-Fallow AEC (Table 5-1). Several factors have contributed to the decline of barley acreage: low barley feed prices ($1.93–$5.10/bu), lack of herbicide-resistant varieties, susceptibility to root and crown pathogens, low grain lysine content (reducing feed quality), and condensed tannins ill-suited for food uses.

Barley end uses include feed, malt, and food; straw and grain are also potential feedstocks for ethanol production. Improved prices and recent interest in food quality barley may offer growers additional market incentives, especially in the drier regions. Development of food quality winter barley cultivars with improved hardiness could provide additional options, and value, to growers in the future (Petrie 2008; Rustgi et al. 2015).

Barley is well-adapted across the region and provides several rotational benefits. For example, barley has a shorter growing season than wheat and may prove more able to avoid the late-season stressors predicted with climate change. Barley can suppress select soilborne pathogens; Oregon studies found that cereal rotations including a spring barley sequence had the lowest root-lesion nematode infection rate (Smiley and Machado 2009). Feed protein requirements are low (10% or less) and the 2 lb N/bu UNR for feed barley is much lower than for wheat, whereas high-quality malt barleys require 11–12% protein and have a slightly higher UNR than soft white wheat. Barley typically has a higher straw-to-grain ratio than wheat, which can enhance soil health and carbon sequestration.

Currently there are no price premiums for high protein barley. However, in response to market interest in the food quality barley niche, Rey et al. (2009) looked into the feasibility of producing high beta-glucan, no-till barley at Moro and Pendleton. Results showed that the high beta-glucan, waxy, hulled varieties 'Salute' and BZ 502-563 performed competitively with the commonly grown feed barleys 'Baronesse' and 'Camas' at both sites, and are a good alternative for dryland cereal producers in the inland PNW. ▲ ■

Integrating Alternate Winter Cereals and Improved Fallow Practices

Alternate winter cereals, such as winter triticale, hard red winter wheat, and facultative wheat and barley, add diversity to traditional soft white winter wheat acreage and are adaptable to the warmer, drier summers predicted for the PNW. Winter crops benefit from a longer growing season, deeper rooting and more efficient utilization of winter precipitation, and earlier grain fill (Pakish et al. 2015; Schillinger et al. 2010). Autumn-sown grains protect soils during winter precipitation and have a higher grain and straw yield potential than their spring counterparts; earlier maturity avoids drought and heat later in the growing season.

Winter triticale

Winter triticale is highly promising as an alternative crop to diversify the Grain-Fallow AEC and is adapted to late-planted, no-till systems. Production may increase the opportunity for adoption of no-till systems in the WW-F region where inadequate seed zone moisture in early fall limits success. Low prices and lack of insurance have limited grower adoption; triticale crop insurance is expected to be available beginning in 2017.

Ritzville, studies found that early-planted winter triticale out-yielded early-planted winter wheat 22% over 6 years (2011–2016); average yields were 5,005 lb/acre and 4,085 lb/acre, respectively (Figure 5-5). Late-planted winter triticale yield (3,735 lb/acre) was similar to early-planted winter wheat (Schillinger, unpublished data, with permission). ▲ ■ Late-planted winter triticale has better yield potential compared to winter wheat, which can suffer 36% yield reduction over early-planted wheat. The crop can be grown with the same equipment and inputs as wheat, and in-crop grass weed herbicides are available for use. Winter triticale produces larger amounts of residue than wheat, has a root mass that is double that of most other cereals, can enhance soil quality and

Figure 5-5. Early-seeded winter triticale (right) out-yields early-seeded winter wheat (left) at Ritzville, WA. (Photo by Bill Schillinger.)

carbon sequestration, and provide erosion protection. Winter triticale has low susceptibility to insect pest and disease problems and good weed competition due to vigorous growth habits, leafiness, and height. Low feed grain prices have limited interest in triticale production in this area in the past, but improved prices support economic opportunity. Triticale can outperform wheat in marginal conditions, produce more biomass, potentially sequestering additional carbon, and is more tolerant of low soil pH and several soilborne pathogens and nematodes. Winter triticale's extensive root mass is effective against erosion (Schillinger et al. 2012; 2015).

Hard red winter wheat

Hard red winter wheat has been an attractive alternative in the Grain-Fallow AEC where yield potential is just marginally less than for soft white winter wheat and growers can more economically achieve the high protein percentage required to garner market premiums. Additional needed N inputs are low due to water stress and lower yield potential in this region. Initially, hard red winter wheat was best adapted to the driest production regions (<9” MAP). However, improved hard red winter wheat varieties with greater yield potential, disease or herbicide resistance may lead to increased production in higher precipitation areas. Depending on relative prices, returns on lower yielding hard red winter wheat can be similar to soft white winter wheat returns (Esser et al. 2008). Adoption of no-till hard red winter wheat is limited in the Grain-Fallow AEC as late planting reduces yield potential. However, no-till studies in Morrow Co. Oregon (4–6’ soil depth and 7.2–9.4” MAP) found that late-planted AgriPro ‘Paladin’ and ‘Norwest 553’ hard red winter wheat cultivars performed well in late-planted situations and yielded similarly to ‘Tubbs’ soft white winter wheat, ranging from 33.6 to 35.4 bu/acre. Recently released cultivars such as ‘Farnum’ have not yet been evaluated for performance in low precipitation, no-till systems. Fallow area producers will benefit from continued development of varieties that perform well under late-planted, no-till systems (Lutcher et al. 2012). ▲ ■

Facultative wheat and barley

Facultative wheat or barley show potential as a replacement for winter wheat in no-till cropping systems where late-planting of winter wheat and annual spring cropping are not feasible. No-till fallow practices can reduce seed zone moisture, delaying winter wheat planting and reducing yield potential compared to conventional till WW-F systems. Facultative cereals can be planted later than winter wheat, thus are better adapted to no-till chemical fallow systems such as FW-ChF or FW-SW-ChF, reducing erosion and enhancing soil health in the Grain-Fallow AEC. Late-planted facultative wheat generally out-yields spring wheat and provides winter cover; facultative wheat is more competitive with summer annual weeds, and appears to be less susceptible to stripe rust and root disease pathogens than spring wheat.

Results from long-term studies at Ralston, showed that a no-till FW-ChF sequence had less yield variability than reduced-till WW-F, but had lower yields and net returns. Facultative wheat is more susceptible to winter damage and provides less winter cover than winter wheat, but begins spring growth and flowering earlier than true winter wheat, potentially avoiding late-season heat and drought stressors. Researchers concluded that FW-ChF shows potential for no-till late planting purposes, but that conservation cost-share incentives would likely be needed for growers to adopt this system, and that further research would be useful (Bewick et al. 2008; Sullivan et al. 2013). ▲ ■

Tall stubble no-till and undercutter tillage systems

No-till fallow systems generally reduce yield potential in the Grain-Fallow AEC due to delayed fall planting in response to excess evaporation from the seed zone compared to conventional tillage. However, studies at Ralston show that replacing semi-dwarf cultivars with tall, high residue winter wheat or triticale and harvesting with a stripper header can support timely fall planting in no-till systems. Tall, standing stubble, and heavy residue, protects the soil surface, reducing wind speed and surface temperature, and conserving seed zone moisture. These improved seeding conditions lead to better establishment of fall-seeded crops; Young et al. (2016a) found that this no-till system improved winter canola establishment 35–40% over reduced-till fallow. ▲ ■

Studies at the Jirava farm (Ritzville) found that seed zone moisture is generally better with undercutter tillage fallow than for standard no-till fallow systems. At Lind (9” MAP), winter wheat yields in a WW-UTF system were 35% greater than yields in the late-planted, no-till winter wheat system. In addition, the undercutter method can reduce blowing dust 70% (Schillinger 2016; Schillinger et al. 2016). ▲ ■

Integrating Flex Cropping

Flex cropping practices provide producers with options to reduce fallow, gain production opportunities, and increase crop biomass, carbon sequestration, and soil surface cover. Adequate moisture, favorable crop prices, and low weed and disease pressures help determine profitability of flex crop options. Growers can assess yield potential for a spring or fall flex crop using soil water content prior to planting, historic precipitation values, and site-specific yield history. Growers may be able to take advantage of late-summer rains to support recrop winter wheat or alternate crops such as winter canola or peas following wheat harvest, or to plant a spring crop during a traditional fallow sequence.

Available soil water and expected crop season precipitation can be useful in determining profitability prior to planting a crop. Schillinger et al. (2012) calculated that wheat requires 2.3" of available water for vegetative growth with an average 5.8 bu/acre production with each additional inch of available water, including stored soil water and spring precipitation. Winter wheat yields following summer fallow increased 7.3 bu/acre with each additional inch of water compared to 5.4 bu/acre for recrop spring wheat. Growers can use this tool to predict wheat yields after summer fallow or recrop spring wheat using the following equations and site or region-specific real-time and historical moisture values:

$$\text{WW after SF: Yield} = 6.7\ \text{SFW} + 7.9\ \text{OWG} + 4.4\ \text{A} + 7.6\ \text{M} + 12.2\ \text{J} - 16.4$$

$$\text{Recrop SW: Yield} = 5.4\ \text{OWG} + 1.4\ \text{A} + 6.4\ \text{M} + 5.7\ \text{J} - 10.6$$

Where Yield is grain yield in bu/acre, SFW is summer fallow available soil water in inches, OWG is net over-winter soil water gain in inches, A is April rain, M is May rain, and J is June rain in inches.

Lutcher et al. (2013) provide excellent guidelines for optional fall or spring flex planting decisions based on soil depth, crop choice, MAP, effective rooting depth of crop, and total plant-available soil water content at planting time. Table 5-11 illustrates the minimum plant-available soil water content needed for successful cropping.

Table 5-11. Recommended minimum plant-available soil water content needed for fall and spring planting.

Average annual precipitation (in)	Minimum plant-available soil water content (in)*	
	Fall planting	Spring planting
<10	3.5	4.5
10 to 12	3.0	4.0
12 to 14	2.5	3.5
14 to 16	2.0	3.0
16 to 18	1.5	2.5
>18	1.0	2.0

Source: Lutcher et al. 2013 Note: Values listed in this table are guidelines only. *Effective rooting depth. Decisions to plant may be based solely on the anticipated quantity and timing of precipitation later in the growing season.

Integrating Cover Crops

Cover crops are "close growing crops such as grasses or legumes that are used primarily to provide seasonal protection against soil erosion and for soil improvement" (Unger et al. 2006). Historically, growers in the inland PNW used green manure cover crops to supplement N before the introduction of chemical fertilizer, as well as to control erosion and provide forage and hay for livestock. Cover crop benefits include maintaining soil organic matter; fixing N, reducing soil evaporation; increasing infiltration; suppressing weed, disease, and pest pressure; improving soil structure; providing soil erosion protection; and promoting cash crop productivity (Snapp et al. 2005).

There is renewed interest in cover cropping to enhance crop diversification and improve soil quality in PNW dryland cereal production systems. Researchers and growers are evaluating cover crop plant biomass production, soil fertility, soil moisture dynamics, and other factors that affect production and profitability of the following cash crop (e.g., winter wheat) and soil quality indicators. Cover crops can offer positive on-farm benefits, but there are major challenges to successful integration in dryland cropping systems including establishment, weed competition, water demand, and effect on yield of subsequent cash crops. Preliminary research results have shown that establishing mixed cover crops after cash crop harvest may be impractical due to soil moisture deficits (Thompson and Carter 2014). Similarly, Roberts et al. (2016) indicated that cover crop mixtures pose a high risk; cover crops may extract excessive water, limiting the available water for the following season's cash crop. Growers may also be reluctant to take on additional labor and operation costs such as seeds, tillage, weed control, and cover crop termination. With no immediate cash return to producers, cover crops need to be further evaluated for intermediate- and long-term economic and cropping system benefits. Research with single and multiple cover crop species are ongoing in various precipitation regions of southeastern Washington and in Pendleton, Oregon. Cover crop mixes that contain cruciferous crop seeds (e.g., mustard, canola, radish) are a potential source of black leg disease caused by the fungal pathogen *Phoma lingam*. Growers should only plant seed that has been tested and certified to be black leg-free.

Research efforts are focused on finding beneficial ways to include cover crops in dryland systems that will complement cash crop production. Some potential cover cropping options in the PNW follow:

1. Companion cover crop grown for a short period with a cash crop.
2. Added biomass can reduce erosion, provide protection from winter freeze, and improve soil organic matter (e.g., seeding low rates of faba bean, radish, and buckwheat with the standard rate of winter wheat; Roberts et al. 2016).
3. Cover crop in reduced or no-till systems. Minimizing tillage intensity can improve water infiltration and reduce evaporative losses, which can counterbalance the moisture utilized by a cover crop.
4. Cover crop as forage.
5. Cover crop mixes and cattle grazing were integrated into small grain and oilseed rotation in a high precipitation region in north-central Idaho (Finkelnburg et al. 2016). The three-year study demonstrated a gain in heifer body weight and winter wheat yield.
6. Plant cover crop in "prevented planting" acreage.
7. Climate change is expected to increase spring precipitation. Excess soil moisture can lead to more frequent delayed or prevented planting acreage; planting a cover crop in lieu of leaving the ground fallow can reduce erosion and improve soil quality without negative financial impact (Steury 2014).

The USDA Natural Resource Conservation Service (NRCS) has recently developed the PNW Cover Crop Selection Tool to help growers and conservation planners select cover crop species adapted to their climate, soils, and intended purposes. More information on the tool and its use can be found in ***http://www.nrcs.usda.gov/wps/portal/nrcs/detail/plantmaterials/technical/toolsdata/plant/?cid=nrcseprd894840***.

Measuring Economic Impacts of Diversification on a Rotational Basis

There are both short- and long-term economic impacts of rotational diversification, and measuring long-term impacts may be difficult. However, longer term impacts, such as increased soil organic matter and therefore increased water holding capacity, may provide a stronger incentive for changing farming practices. This section discusses short- and long-term costs and benefits of diversifying your cropping system.

Short run costs of changing cropping systems will typically involve some management challenges:

- Growers will need to evaluate potential alternative crops and varieties, along with accompanying changes in pest control, marketing, and other factors.
- A new crop or management practice may require either adapting current machinery or purchasing new machinery.
- A new crop or management practice will involve some increase in risk as well as additional management.

Short run benefits of changing your cropping system might include:

- Reduced weed, disease, or insect problems
- Modified spring or fall workload
- Ability to take advantage of strong market prices, or avoid weak market prices

Long run benefits of changing your typical cropping system may include:

- Reduced erosion
- Improved soil health
- Reduced risk associated with a more diverse portfolio of potential crops
- Increased returns due to increased flexibility with respect to timing of fallow operations

Several farmers in the region who converted to no-till many years ago are finding that their soils are able to support a more diverse crop mix today due to improved soil health. The rotational diversity they use today would not have been possible without earlier efforts to improve their soil. In grain-fallow areas where no-till may result in excessive evaporation of seed zone moisture, improved fallow practices and flex cropping can support diversification. Grower case studies are available online at ***http://pnwsteep.wsu.edu/dscases*** and ***https://www.reacchpna.org/case_studies***.

Enterprise budgets and worksheets for each rainfall zone are available to compare annual profitability by cropping system and are referenced below. Measuring average annual profitability for diverse rotations allows economic comparisons across rotations with varying lengths. Adjusting budgets to reflect rotational impacts can be done by changing crop yields, prices, herbicide use and other assumptions in specific worksheets. Many different rotational scenarios can be created, and the resulting comparisons will be calculated automatically in the summary tab of the worksheet. The following sections discuss budget scenarios comparing profitability for each dryland AEC (Painter 2016a; 2016b; 2016c). Since the relative economics of crop choices vary each year, all examples use 5-year average prices (2011–2015) received by PNW farmers.

In a detailed economic analysis of net returns by crop under conventional tillage for the Annual Crop AEC, (Painter 2016a; 2016d), assuming typical yields and prices as stated in Table 5-12, soft white winter wheat, chickpea, and hard red spring wheat were the most profitable crops, averaging $60/acre or more net returns over total costs. Austrian winter pea, soft white spring wheat, and lentil averaged $32, $27, and $18/acre, respectively, whereas net returns were negative for pea and spring barley at –$7 and –$24/acre, respectively, and lowest for spring canola at –$35/acre, based on the assumptions and underlying budget values in the Painter (2016a) worksheet. ●

However, on any one piece of land, average net returns over time need to be calculated on a rotational basis. Farmers rotate crops for many reasons, including reducing disease and pest issues, and to improve overall soil health and crop yields. Average net returns by rotation are calculated as a simple average of net returns by crop (Figures 5-6, 5-7, and 5-8) and may reflect rotation benefits to subsequent crops. In the Annual AEC, net returns were highest for a rotation of soft white winter wheat, hard red spring wheat, and chickpea, averaging $62 per rotational acre per year, and lowest for a rotation of winter wheat, spring barley, and spring canola, at $2/acre/year (Painter 2016a).

On a crop-by-crop basis, choices such as peas, barley, or canola appear unprofitable, but from a rotational or longer term standpoint, these crops may improve overall profitability. For example, research shows

Table 5-12. Crop yield and price assumptions and net returns over total costs by crop for the Annual Crop agroecological class, 2011–2015 average farmgate prices. ●

Annual Crop ●	Unit	Yield unit/ac	Price $/unit	Net Return $/ac/yr[1]
Soft White Winter Wheat	bu	80	$6.44	$64
Soft White Spring Wheat	bu	58	$6.44	$27
Hard Red Spring Wheat	bu	58	$8.41	$60
Spring Barley	ton	1.5	$188.00	–$18
Pea	lb	1700	$0.19	–$7
Lentil	lb	1100	$0.30	$18
Chickpea	lb	1200	$0.34	$63
Spring Canola	lb	1500	$0.21	–$35
Austrian Winter Pea	lb	2000	$0.22	$32

[1]Net returns over total costs using 2013 input costs.

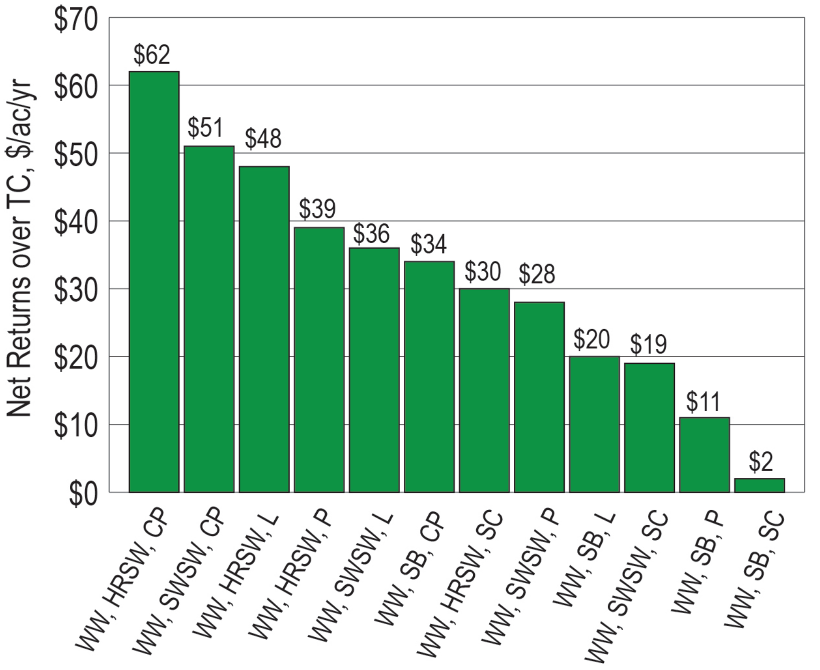

Figure 5-6. Average annual profitability, expressed as net returns over total costs (TC), for the Annual Crop agroecological class, 2011–2015 average farmgate crop prices. ●

a yield increase in wheat following peas and canola of 19% and 15%, respectively (Guy and Karow 2009); or, use of an herbicide-tolerant canola crop can reduce persistent annual grass weeds, increasing subsequent crop yields and reducing herbicide costs.

Detailed enterprise budgets and worksheets for low rainfall (Connolly et al. 2015a; 2015b) and intermediate rainfall (Connolly et al. 2016a; 2016b) regions, include an oilseed rotation and a grain rotation and separate wheat budgets for each. These budgets were adapted to reflect 2011–2015 average farmgate crop prices in the following profitability scenarios (see Painter 2016b; 2016c).

In the Transition AEC example, net returns over total costs were highest for a 45-bushel hard red spring wheat crop, averaging $47/acre (Table 5-13). Net returns for an 86-bushel winter wheat crop in the oilseed rotation (F-SWWW-SC) were $58/acre, but this included the costs of the preceding fallow year, so it is a 2-year return (Painter 2016b). ▲

The predominant crop sequence in the Transition AEC is a 3-year F-SWWW-SWSW rotation. Diversifying from this rotation to include an oilseed such as spring canola (F-SWWW-SC) can provide many rotational benefits, from reducing disease and weed pressure to breaking up hardpan layers and improving nutrient cycling. Assuming a 10% yield advantage for winter wheat in the oilseed rotation, and replacing the spring wheat crop with a spring canola crop, net returns for the 3-year period average $19/acre/year, compared to $16/acre/year in the F-SWWW-SWSW rotation, or $25/acre for F-SWWW-HRSW (Figure 5-7). Thus, the oilseed rotation is competitive with the grain rotation under the assumption of a 10% yield advantage for soft white winter wheat.

In the Grain-Fallow AEC example, net returns over total costs for 2011–2015 using five-year average prices for PNW farmers were greatest ($16/acre over a 2-year period) for soft white winter wheat preceded by summer fallow in a 4-year oilseed rotation (F-WC-F-SWWW), which assumes a 10% yield advantage for winter wheat (Table 5-14; Painter 2016c). The standard 2-year (F-SWWW) cropping system showed net returns over total costs of –$6/acre over a 2-year period (–$3/acre/year), which is not an economically sustainable system. For winter canola

Table 5-13. Crop yield and price assumptions and net return over total costs by crop for the Transition agroecological class, 2011–2015 average farmgate prices. ▲

Transition ▲	Rotation[1]	Unit	Yield unit/ac	Price $/unit	Net Return $/ac[2]
Soft White Winter Wheat	OR	bu	86	$6.44	$58
Spring Canola	OR	lb	1500	$0.21	–$2
Soft White Winter Wheat	GR	bu	78	$6.44	$30
Soft White Spring Wheat	GR	bu	50	$6.44	$18
Hard Red Spring Wheat	GR	bu	45	$8.41	$47
Spring Barley	GR	ton	1.5	$188.00	$4

[1]OR = oilseed rotation with canola (F-WW-SC); GR = grain rotation (F-WW-SW or SB)
[2]Net returns over costs using 2013 input costs.

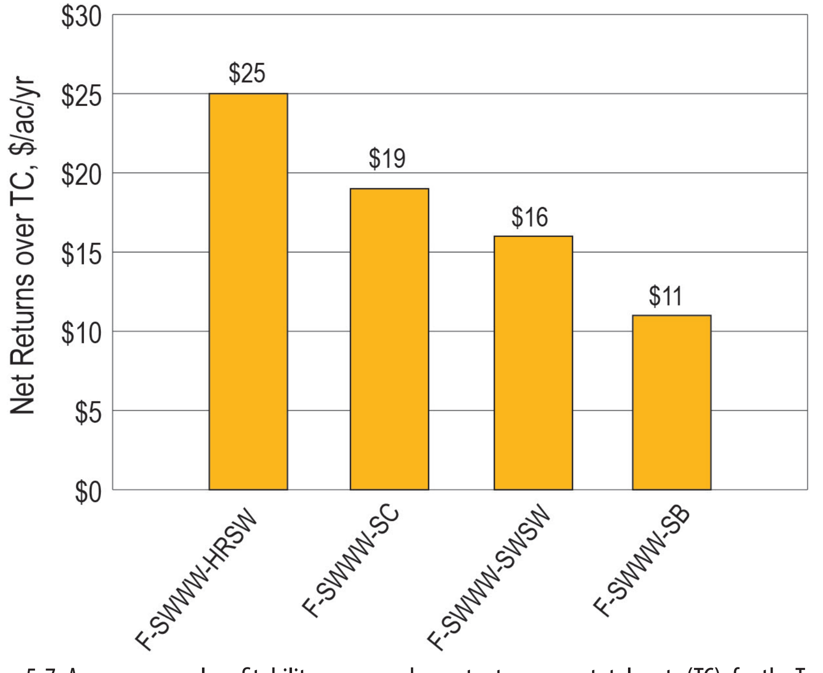

Figure 5-7. Average annual profitability, expressed as net returns over total costs (TC), for the Transition agroecological class, 2011–2015 average farmgate prices. ▲

preceded by summer fallow (F-WC), average returns over total costs were even less profitable at –$22/acre over a 2-year period. ■

For the 4-year oilseed rotation (F-SWWW-F-WC), average net returns over total costs were –$1/acre/year (Figure 5-8), assuming the 10% average yield advantage for soft white winter wheat, compared to –$3/acre/year for the standard cropping system of F-SWWW. The 10% yield advantage for winter wheat in the oilseed rotation is attributed to a more diversified rotation, particularly beneficial in the presence of problems such as persistent grass weeds or wheat disease. Lack of profitability in both of these systems highlights the production challenges in the Grain-Fallow AEC.

Obviously, economic feasibility is critical to sustainability. Growers are not motivated to plant spring and winter canola if estimated net returns over total costs are negative. When spring canola prices were rising between 2008 and 2012 (Figure 5-9), planted acreage of this crop responded, just as chickpea acreage expanded in response to the high relative expected returns from this crop. However, annual production of winter wheat across all AECs typically occurs on more than 40% of the total acreage. Continuous cropping of small grains results in yield decline and decreased returns. Relatively small gains in yields or cost savings can make diversification into alternative crops economically advantageous. Producers may be willing to grow a less profitable crop in the current year to increase resiliency and economic returns in subsequent years, particularly if they can use tools such as these budget worksheets to estimate impacts under different assumptions. Quantifying the potential risks and benefits associated with new crops or rotations may be an important step in convincing growers, bankers, landlords, and other farming partners to try new practices for enhancing overall sustainability.

Table 5-14. Crop yield and price assumptions and net returns (2-year) over total costs for the Grain-Fallow agroecological class, 2011–2015 average farmgate prices. ■

Grain-Fallow ■	Rotation[1]	Unit	Yield unit/ac	Price $/unit	Net Return $/ac[2]
Winter Canola	OR	lb	1500	$0.21	-$22
Soft White Winter Wheat	OR	bu	50	$6.44	$16
Soft White Winter Wheat	GR	bu	45	$6.44	-$6

[1]OR = oilseed rotation with canola; GR = grain rotation
[2]Net returns over costs ($/acre, 2-year crop-fallow cycle) using 2013 input costs.

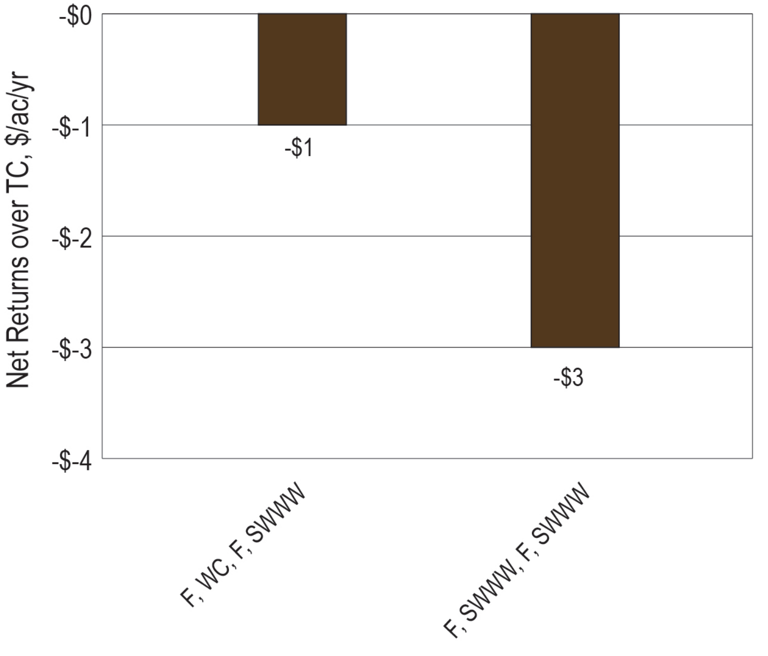

Figure 5-8. Average annual profitability, expressed as net returns over total costs (TC), for the Grain-Fallow agroecological class, 2011–2015 average farmgate prices. ■

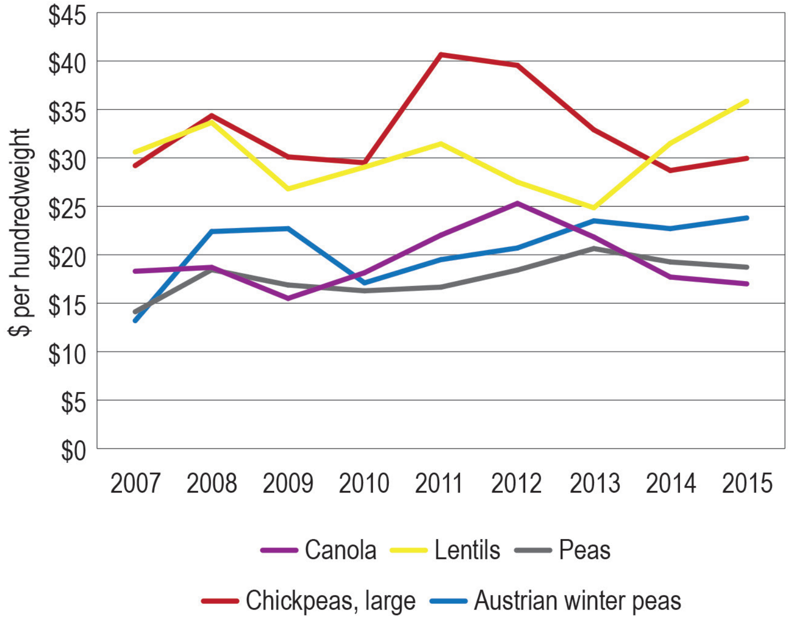

Figure 5-9. Prices received by growers for alternate crops in the PNW (NASS data).

Grower Resources

Oregon State University AgBiz Logic Website

http://www.agbizlogic.com/

Oregon State University Wheat Research Website

http://cropandsoil.oregonstate.edu/group/wheat

REACCH Farm Enterprise Budgets

https://www.reacchpna.org/farm-enterprise-budgets

REACCH Grower Case Studies

https://www.reacchpna.org/case_studies

STEEP Grower Case Studies

http://pnwsteep.wsu.edu/dscases/

University of Idaho Brassica Breeding and Research Website

http://www.cals.uidaho.edu/brassica/index.asp

University of Idaho AgBiz Website

http://www.uidaho.edu/cals/idaho-agbiz

STEEP Grower Case Studies

http://pnwsteep.wsu.edu/dscases/

Washington State University Washington Oilseed Cropping Systems Website

http://css.wsu.edu/biofuels/

Washington State University Small Grains Website

http://smallgrains.wsu.edu/

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Table 5-A1. Potential alternative crops for direct seeding in the inland Pacific Northwest by agroecological class.

	Annual Crop ●	Transition ▲	Grain-Fallow ■
Winter cereals			
Oats	5	3	2
Triticale	5	5	5
Winter broadleaf			
Faba bean	3	2	2
Flax	4	3	3
Lentil	4	4	3
Lupine	3	3	3
Pea	4	3	3
Canola/rapeseed	5	5	5
Cool season spring cereals			
Oats	5	3	2
Triticale	5	5	5
Cool season spring broadleaf			
Chickpea	5	3	2
Crambe	5	4	3
Dry pea	5	3	2
Faba bean	3	2	1
Flax	4	3	3
Lentils	5	4	3
Lupine	4	4	3
Mustard	5	5	4
Canola/rapeseed	5	4	3
Warm season summer grasses			
Corn	4	3	3
Millet	4	4	3
Sorghum	4	4	3
Warm season summer broadleaf			
Buckwheat	4	3	1
Dry beans	5	3	1
Safflower	4	3	2
Soybean	3	2	1
Sunflower	4	2	2

1 = definitely not; 3 = possibly; 5 = definitely. Adapted from Guy and Karow (2009).

Table 5-A2. General soil water holding capacity (SWHC), soil organic matter (SOM), and crop productivity characteristics by agroecological class.

	Annual Crop ●			Transition ▲			Grain-Fallow ■		
SWHC (in/ft)[1]	2.0–2.4			1.8–2.2			1.6–2.0		
SOM (%)[1]	3–4			2–3			<1.5		
	Grain bu/ac	Grain lb/ac	Residue lb/ac	Grain bu/ac	Grain lb/ac	Residue lb/ac	Grain bu/ac	Grain lb/ac	Residue lb/ac
Small grains									
Winter wheat[1,2]	80–120 (90)	5400	7180	60–80; 30–40	4200; 2100	6090; 3549	40–60	3000	4440
Spring wheat[1,2]	75	4500	5580	55; 25	3300; 1500	4389; 2535	40	2400	3360
Winter barley[2]	125	6000	5700	93; 32	5200; 1800	6136; 4050	60	3500	5250
Spring barley[2]	110	5300	4929	83; 30	4700; 1700	4700; 2992	34	1900	3040
Winter triticale[3]	—	—	—	—	—	—	78	4890–6660	—
Hard red spring[4,5]	—	—	—	45	4700	—	—	—	—
Hard red winter[4,5]	—	—	—	73	4400	—	45	4700	—
Grain legumes									
Spring dry pea[2]	—-	2200	28601	—	1600	2560	—	—	—
Winter dry pea[6]	—	4000-5000	—	—	3500	—	—	1500	—

Table 5-A2 (continued). General soil water holding capacity (SWHC), soil organic matter (SOM), and crop productivity characteristics by agroecological class.

	Annual Crop ●			Transition ▲			Grain-Fallow ■		
SWHC (in/ft)[1]	2.0–2.4			1.8–2.2			1.6–2.0		
SOM (%)[1]	3–4			2–3			<1.5		
	Grain bu/ac	Grain lb/ac	Residue lb/ac	Grain bu/ac	Grain lb/ac	Residue lb/ac	Grain bu/ac	Grain lb/ac	Residue lb/ac
Spring Lentil[2]	—	16002	2720	—	1200x	2400	—	—	—
Winter lentil[6]	—	3000	—	—	—	—	—	—	—
Chickpea[6]	—	2000	—	—	—	—	—	—	—
Oilseeds									
Spring canola[7,8]	—	2000	5142	—	1500	3850	—	500	1285
Winter canola[7,8]	—	3000	7700	—			—	15005	
Camelina[9]	—	1500	3850	—	1050	2700	—	850	2185
Yellow mustard[10]	—	2000	5142	—	1500	—	—	<1200	—
Safflower[11]	—	3000	—	—	1500	—	—	500	—

Note: lb per bushel: wheat (60); triticale (56); barley (48); oats (32); sunflower (24-32); rapeseed (60); flax (60).
[1]Douglas et al. 1999; Table 5.2 p. 76. [2]Douglas et al. 1999; Table 5.3 p. 87. Residue calculated using residue-to-grain ratios for cereals and pea and lentil zones 2, 3, and 5. [3]Schillinger et al. 2015. [4]Connolly et al. 2016. [5]Connolly et al. 2015. [6]Ranges supported by various USDA variety trials. [7]Brown et al. 2009. [8]Oilseed residue values calculated using Grain*HI (0.20–0.35) = Biomass, and Residue = Biomass–grain. [9]Hulbert et al. 2012; Expected camelina yield = 70 lb/ac grain per inch annual precipitation. [10]J. Brown et al. 2005; Expected yellow mustard yield = 95 lb/ac grain per inch precipitation: 20” ppt = 1,900 lb/ac; 16” ppt = 1,520 lb/ac; 12” ppt = 1,140 lb/ac. [11]Petrie et al. 2010.

Table 5-A3. Typical nitrogen (N) requirements and relative water use.

<table>
<tr><th></th><th>UNR
lb N/bu</th><th>UNR
lb N/100 lb</th><th colspan="2">Relative Water Use[2,3]</th></tr>
<tr><td>Soft white wheat[1]</td><td>2.7–3.6</td><td>4.5–6.0</td><td rowspan="3">Winter wheat, winter triticale, winter canola</td><td rowspan="3">Highest</td></tr>
<tr><td>Hard red wheat[2]</td><td>3.0–3.7</td><td>5.0–6.2</td></tr>
<tr><td>Feed barley[2]</td><td>2</td><td>4.1</td></tr>
<tr><td>Malt barley[2]</td><td>3</td><td>6.2</td><td rowspan="2">Sunflower, safflower, chickpea</td><td rowspan="2">↓</td></tr>
<tr><td>Triticale[3]</td><td>similar to SWWW</td><td>—</td></tr>
<tr><td colspan="3">Broadleaf</td><td rowspan="2">Spring cereal, spring mustard, canola, and camelina</td><td rowspan="2">↓</td></tr>
<tr><td>Canola[4]</td><td>—</td><td>7
(6.0–10.7)</td></tr>
<tr><td>Camelina[5]</td><td>—</td><td>5–6</td><td rowspan="2">Lentil</td><td rowspan="2">↓</td></tr>
<tr><td>Safflower[6]</td><td>—</td><td>5</td></tr>
<tr><td>Yellow mustard[7]</td><td>—</td><td>8–12</td><td>Pea</td><td>Lowest</td></tr>
</table>

[1]Koenig et al. 2005.
[2]Wysocki et al. 2006.
[3]Schillinger pers. comm.
[4]Koenig et al. 2011; Karow 2014.
[5]Hulbert et al. 2012.
[6]Armah-Agyeman et al. 2002.
[7]J. Brown et al. 2005; Davis and Wysocki 2010.