Optimized production practices for winter canola (*Brassica napus* L.), and rotation effects of winter and spring canola in Northern Idaho

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Authorization to Submit Thesis

This thesis of Eric Ireton, submitted for the degree of Master of Science with a Major in Plant Science and titled "Optimized production practices for winter canola (*Brassica napus* L.), and rotation effects of winter and spring canola in Northern Idaho," has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Pacific Northwest (PNW) agriculture is dominated by small grain cereal production systems. Ranking highest in national wheat yield per area plus more than 100 years of experience growing wheat might explain why agriculture is one dimensional in this region. However, there is growing concern about the reliance on small grain cereal production because cereal pest and grass weed pressure continues to increase; increasing the cost of production and lowering yields. Diversifying production systems increases soil health and small grain cereal yields but has not been shown to be the most economically successful strategy to help farmers meet their bottom line. There are limited successful alternative crops adapted to the Pacific Northwest climate. Grain legume and *Brassica* crops have shown the greatest potential for rotating with winter wheat, the most predominate cereal crop. *Brassica* species are grown on limited hectares because farmers' lack familiarity with the crop, and because of a history of crop failure. However, *Brassica* crops like canola have unique sustainability rotation benefits and have greater yield potential in the PNW than any other US area. This study is designed to analyze the viability of canola in winter wheat rotations compared to other rotation strategies and to determine best management practices that will optimize production and grower returns of canola in the PNW.

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Lastly, I want to thank my family and friends for being constant sources of reassurance and love throughout my graduate school experience.

Dedication

I dedicate this thesis to all farmers and scholars whom
can utilize its value to better the world, near and far.

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Chapter 1: Introduction

Canola is the second most produced oilseed in the world, behind soybeans. Almost 22 million ha of canola were planted in Canada, China, and India combined in 2017. The healthy fatty acid profile and relatively high smoke point make canola ideal for all cooking needs. Although the US is a leading consumer of canola oil less than 1 million ha of the crop is grown in the country.

US canola production initially rose rapidly after the FDA granted Generally Regarded As Safe (GRAS) status for the crop in 1985, with 54,633 ha planted in 1991, 18,8584 ha in 1995, and 607, 000 ha in 2001. However, US canola acreage increases been very modest since 2011, and production have leveled between 607,000 and 688,000 ha.

Most of the US canola is spring canola grown in North Dakota. North Dakota environmental similarities to Canada have made it easier for farmers to incorporate the crop into existing rotations. Although North Dakota accounts for almost 85% of US canola acres, canola yield is consistently higher in the PNW region. In Idaho, 2016, average spring canola yield was 2,100 kg ha^{-1}, whereas, North Dakota averaged 1,840 kg ha^{-1}.

Few crops have shown adaptation to the environmental conditions of the Pacific Northwest (PNW) dryland agriculture, where small grain cereals predominate, with winter wheat planted on over 80% of acres. Wheat growers in the PNW have consistently produced high yields year after year. However, predominance of wheat crops in the region has led to greater incidence of cereal diseases, pests, and grass weeds. Although effective soil management, increased fertilizer and chemical pesticide inputs, and precision agriculture has off-set the need to widen crop rotations in this area, the need for research and education on sustainable agriculture is great because cereal grain yields continue to decline in mono-cropping system. Indeed, many believe that the wheat-fallow and wheat-wheat rotations that predominate in the PNW are not long-term sustainable.

Winter canola has many benefits in wheat rotations. It allows for disease, insect, and weed cycles to be broken because it is a dicot. The unique root structure as well as high amounts of residue contribute to erosion prevention. One of the major limiting factors for winter canola is inconsistent establishment and performance each year. In addition, alternative crops in rotation with winter wheat must be as economically competitive as mono-cropping wheat and other spring crop options for PNW farmers to consider including the new crops.

This project will: (1) determine best management practices for winter canola to maximize productivity and grower returns, Chapter 2; and (2) will quantify the value of including winter and spring canola into winter wheat rotations by comparing various two-year rotations for production and grower profit, Chapter 3.

The aim of study (1) is to determine the effect of winter canola cultivar, seeding date (with and without forage harvest), row spacing, and seeding rates that optimize production and grower profitability. Specific objectives of study (1) include:

- To determine whether seed yields are significantly higher if crops are planted early (late July to early August) or if planted late (late August to early September).
- To determine whether it is more economically beneficial to use winter canola as a dual-purpose (forage plus seed) crop or only harvest seed.

- To determine whether seed and forage biomass yields are significantly higher if crops are planted at low (3.4 kg ha^{-1}) or high (5.6 kg ha^{-1}) seeding rates and narrow (25 cm) and wide (50 cm) row spacing.

The aim of study (2) is to determine the rotation effects of winter and spring canola by examining the effects of; (a) spring canola-winter wheat; spring pea-winter wheat; spring barley-winter wheat, and spring wheat-winter wheat rotations; and (b) winter canola-winter wheat; Austrian winter pea-winter wheat; summer fallow-winter wheat; and winter wheat-winter wheat two-year rotations of crop productivity and grower profitability. Specific objectives of study (2) include:

- Determine the rotation effect of spring and winter crops on the yield of following winter wheat crops in a two-year rotation.
- Determine the effect of rotation crop on post-harvest water infiltration and soil fertility, which may impact the performance of following winter wheat crops.

Chapter 2: Optimized production practices (planting date, row spacing, seeding rate, variety, simulated grazing) of winter canola (*Brassica napus* L.) in Northern Idaho

2.1 Abstract

Few crops have shown adaptation to the environmental conditions of the Pacific Northwest (PNW) dryland agriculture, where small grain cereals predominate, with winter wheat planted on over 80% of acres. The predominance of wheat being planted is suspected to have reduced sustainability compared to potentially diverse rotations. Winter canola has shown good potential in the PNW when rotated with winter wheat (see next chapter). However, winter canola is relatively new to the PNW and many farmers are not familiar with best management practices (BMP) to maximize yield and profitability. Factors which impact production and profitability of winter canola production include: (1) cultivar choice; (2) planting date; (3) row spacing; (4) seeding rate; and (5) crop management. We investigated the impact of these agronomic factors on yield at two locations over three years. Trials at each location were conventionally tilled, fertilized according to recommended practices, and pests and diseases controlled with appropriate application of pesticides. Canola was planted early (July) and late (September) at two locations over three years. Two commercial hybrids and two open-pollinated cultivars were examined. Plots were planted using narrow and wide row spacing with either high or low seeding rates. Variables recorded included seedling plant stand counts, fall crop establishment, winter kill, days from January 1st to 50% flower bloom, plant height, and seed yield. In fall, half of the early planted plots

were mowed and forage yield (biomass of plant tissue) recorded. At maturity, each plot was swathed prior to harvest. Seed was dried post-harvest in dryers then weighed to determine yield. Results indicate that growers can employ two strategies depending on whether they utilize canola as forage and seed or for seed only. Variety had the largest effect on seed yield. Seedling plant stands were significantly higher under wide spacing, and when planted late. Plant stand was also significantly affected by variety. Crop establishments for spacing, rates, and planting dates were all rated within one point out of nine. Winter survival was higher when canola was planted late. Flowering date was slightly affected by planting date and highly affected by variety. Late planted crops were statistically taller on average and variety impacted height statistically. Forage yields were higher with wide spacing. Seed yield was statistically higher when a low seeding rate was used. Seed yield was significantly affected by variety. Other agronomic factors (seeding rate on forage, cultivar on forage, row space on seed yield, mow on seed yield) were not statistically significant. When harvesting seed alone, the highest seed yield, 5,042 kg ha^{-1}, was produced from planting Mercedes, planted late in the fall, at wide spacing, and a low seeding rate. The next highest yield (4th among seed only) from the other varieties was Amanda, planted late, at narrow spacing, and a high seeding rate, 4,271 kg ha^{-1}. Canola utilized as a forage and seed crop had greater gross returns than when only seed was harvested. Highest gross returns from harvesting only seed was from Mercedes, and returned \$1,899 ha^{-1}, whereas, the lowest rated dual-purpose treatment returned \$1,909 ha^{-1}. The highest dual-purpose crop gross return was from planting Amanda planted early, at wide spacing, and a high seeding rate, harvesting forage, which returned \$3,012 ha^{-1}. The next highest performing treatment using any of the other varieties was WC15.7.5 planted early, at wide spacing, with a low seeding rate, harvesting forage, which returned \$2,871 ha^{-1}. In conclusion, winter canola growers in the PNW should plant Amanda, plant early so forage material can be used as supplemental income, at wide row spacing, with a high seeding rate in order to best optimize their economic gross crop return.

2.2 Introduction

2.2.1 Pacific Northwest (PNW) Dryland Agriculture

The PNW is characterized as a Mediterranean climate with wet winters and dry summers (Skidmore and Woodruff, 1968). More than 60% of the precipitation occurs between November and March with a range of 200 mm to 600 mm of annual precipitation (Papendick *et al*, 1983). In the dryland regions rainfall is the most limited factor affecting agricultural production (Granatstein, 1992). Winter months experience freezing temperatures and snow sequences combined with rain and complete thawing (Reed, 2015). Roughly 70% of dryland cropping area has 8-30% graded slopes and in extreme areas slopes can exceed 50% (Papendick *et al*., 1983).

The PNW topography, climate, and agricultural practices contribute to extreme erosion. As of 1995, it was estimated that 40% of top soil was already been lost to erosion (Pimentel *et al*., 1995). Good soils combined with the Mediterranean climate is conducive for excellent small grain production making the region the top yielding in the US, and one of the top dryland grain production regions of the world.

Over the past 40 years, several alternative crops have been evaluated in the region to offer growers an alternative to small grain cereals and broaden crop rotation options.

However, few non-cereal crops have shown good agronomic or economic adaptation to the growing conditions, and crop rotations remain limited and challenging (Yorgey and Kruger, 2017). The few crops that have shown adaptive potential to the dryland conditions include legumes (pea, lentil and garbanzo bean) and *Brassica* (canola, rapeseed and mustard) crops (Pan *et al.,* 2017), but only winter canola has good potential in the lower rainfall regions where legume production is limited. Although, one farm with low rainfall near Ritzville, WA (28 cm annual rainfall) saw winter pea yields of 2,565 kg ha^{-1} over three years (Schillinger *et al.,* 2014). Comparatively, winter canola planted in Odessa, WA (28 cm annual rainfall) yielded 5,121 kg ha^{-1} on average in the 2016 Pacific Northwest Canola Variety Trial (Davis *et al.,* 2016).

2.2.2 Continuous cereal (monoculture) production

Winter wheat is grown on more than 80% of planted acres in the dryland PNW (Schillinger *et al.,* 2003). A winter wheat-fallow cropping system dominates the low rainfall areas of the PNW, because of economic incentives which include “commodity subsidies, farm programs, and global markets” (Roesch-McNally, 2018). However, reliance on a single crop market makes farmers susceptible to price volatility (Kirby *et al.,* 2017). Agricultural trends dating back to the 1950’s indicate rising production costs and static grain prices are making cereal-fallow cropping systems less profitable (Duff *et al.,* 1995). Over the past 100 years of cereal grain production in the PNW farmers’ have gained additional experience and technologies creating more effective implementation of the region’s best management practices (BMP) which has sustained high grain productivity.

Almost 80% of the 3.4 million acres of wheat are soft white varieties, 12% are hard red, and 8% are club (very soft white) cultivars. (USDA NASS, 2017). The state of Idaho produces 25% of US barley, 4% of the nation's winter wheat, and 5% of the nation's spring wheat (ISDA, 2015).

However, continuous monoculture cereal production, classified as a previous wheat field that has wheat planted on it, or when wheat is rotated with other cereals, can cause increased disease and pests, in particular grass weeds (Krupinksy *et al*., 2004). Monoculture cereal production combined with intensive tillage management of traditional fallow degrade soil health and long-term sustainability of PNW small grain production (Machado *et al*., 2007).

Controlling grass weeds and volunteer cereals is paramount for prevention of common cereal diseases and insects because crop residue hosts many diseases and insects. Thus, controlling grass weeds during fallow is essential for effective cereal production (Hirnyck, 2003). Conventional tillage winter wheat-summer fallow systems that dominate the PNW also deplete soil organic carbon, increase soil erosion, and is not biologically sustainable (Rasmussen *et al*., 1980; Rasmussen and Parton, 1994; Reicosky *et al*., 1995; Rasmussen *et al*., 1998). Downey brome, jointed goatgrass, and feral ryegrass populations decrease yields and are difficult to control when the weed cycle is not disrupted. Annual broadleaf weeds can be more easily controlled by pesticide applications.

2.2.3 Potential of canola in PNW

Canola and rapeseed have many edible and industrial uses (Downey, 1966). Canola oil is used for frying, salad dressing, shortening, non-dairy fat substitutes, pet foods, and even supplemental vitamin E. Industrial (rapeseed) uses include: lubricant, greases, plastics, bio-fuel feedstock, printing inks, lacquers, detergents, emulsifiers, fertilizers, pesticides, and use in asphalt (Downey, 1966). Compared to soybean meal, canola has less crude protein, more crude fiber, lower digestible and metabolizable energy, and has high concentrations of minerals and vitamins that are of major importance when formulating animal diets (Downey and Bell, 1990).

Canola has shown good adaptability in the PNW when rotated with winter wheat (see next chapter); however, canola acreage in the region remains relatively low. Increased interest by the general public and at the governmental level in biofuel and canola food oil (Pan *et al.*, 2016) has "increased canola research, extension and production" (Pan *et al.*, 2017), and current value of canola compared to wheat is an important consideration. The addition of a new oil seed crush facilities at Warden, WA, has further increased demand for canola production in the PNW.

Total US vegetable oil consumption was 17.2 million Mt, in 2017. Canada exported 574,000 Mt of seed, 1.9 million Mt of canola oil, and 3.4 million Mt of canola meal with a total value of $3.7 billion (Canola Council of Canada, 2018). In contrast, canola production in the PNW is very small where Idaho produced 17,146 Mt of harvested seed, Oregon 1,470 Mt, and Washington 16,964 Mt in 2015 (USDA, NASS, 2015). This total production is only a fraction of the crushing capacity of the Warden, WA oil seed crush facility which has a crush capacity of 350,000 Mt annually (PCC, 2018). Grower interest combined with better cultivars has resulted in higher acreage of canola over the past few years. However, most of US canola production remains spring canola produced in North Dakota.

There is also a high demand for canola as livestock feed (either seed meal or forage) in the PNW which has an increasingly large dairy industry. For example, there are 2,400,000 head of cattle in Idaho (USDA NASS, 2018), and in 2017 Idaho was ranked 3rd, behind California and Wisconsin for total milk production (USDA, 2018). With extensive small grain production, it is not surprising growers are looking for economically viable ways to diversify their rotations with legumes or Brassicaceae crops (Reed, 2015).

Canola can be planted and harvested using the same equipment as used for small grain cereal production and including canola into crop rotations requires few growing input costs. (Nelson and Grombacher, 1992).

2.2.4 History of canola and rapeseed

The earliest evidence of rapeseed and mustard (*Brassica rapa* and *B. juncea*) domestication comes from India, over 3,000 year ago. The crop spread to China and Japan 2,000 years ago (Hougen and Stefansson, 1983), and rapeseed has been an edible oilseed crop in Asia since. Domestication of rapeseed in Europe coincided with the start of the *Industrial Revolution* where it was discovered that the stability of rapeseed oil in the presence of water and high temperatures meant that it was an ideal lubricant oil for steam engines. This lubricity characteristic also led to a rapid increase in rapeseed acreage in Canada during World War II, to produce oil to lubricate Allied naval steam engines. After 1945 the need for steam engine lubricants dropped dramatically and there was a strong push to develop edible uses rapeseed oil in western society (Shahidi, 1990).

High levels of erucic acid was thought to have negative effects in the human diet, and high glucosinolate content in the seed mean reduced palatability of seed meal to livestock and both quality factors reduced the value of rapeseed crops. In 1974, Canadian new rapeseed varieties were developed as '*double low*' meaning they had less than 2% erucic acid in seed oils, and less than 30 μmoles of total glucosinolates gram^{-1} of defatted seed meal (Bell, 1984; Riggins *et al.*, 1992). When introduced to agriculture these 'edible cultivars' were differentiated from rapeseed and called canola. No deleterious adaptability effects have been discovered in canola since decreasing erucic acid and glucosinolate levels (Downey, 1990).

In 1985, the US food and drug administration granted '*double low*' rapeseed as Generally Regarded As Safe (GRAS) status (NARA, 1985). Prior to obtaining GRAS status (in 1985) edible rapeseed could not be produced in the US and fewer than 20,000 hectares of rapeseed were cultivated in the US. The University of Idaho worked with the US Department of Energy from 1985-1989 to identify regions in the US that were adapted to winter canola production.

Inconsistent seed yields and poor winter survival in the PNW can occur because of poorly established fall plant stands (Walsh, 2012) reducing acreage of the crop. Until recently, there was a lack in locally adapted cultivars for growers to choose from. In addition, few pesticides were registered on canola to counter, weeds, pests and diseases that proliferate in the area. In the case of diseases, there has been limited pressure until recently. Grower education programs have been limited. There was a lack of vertical integration for the vegetable oil industry. All these factors combined with fluctuations of oilseed prices help explain why canola is not as spread through the PNW as it could be (Raymer *et al.*, 1990).

Soil moisture at planting winter canola is critical to successful establishment of the crop before winter. Canola requires higher soil moisture for establishment and emergence than wheat or barley (Kephart and Murray, 1990). Areas of the PNW that receive less than 350 mm can experience disrupted establishment from the lack of moisture (Ehrnsing, 2008). Soil moisture in summer fallow drops dramatically in late summer and early fall. Researchers from the University of Idaho began experimenting with early planting canola 11 years ago to determine if establishment from this earlier seeding was enhanced with higher soil moisture, plus lower soil temperatures and longer growth prior to the onset of winter (Reed, 2015).

2.2.5. Rotation benefits of canola in crop rotations

Diversifying cereal crop rotations has been shown to be both environmentally and economically beneficial (Peterson and Rohweder, 1983). Wheat seed yields following crops other than wheat are normally higher than when wheat following wheat (Angus *et al*., 2015). One major benefit of canola in a cereal rotation is that is a broadleaf. Broadleaf crops can break up disease, insect, and weed cycles in cereal crops, reducing their populations (Liebman and Dyck, 1993; Krupinsky *et al*., 2004; Bushong *et al*., 2012). Different modes of action herbicides can be used on dicots compared to monocots which decreases the chance of developing grass weeds herbicide resistances (Esser and Hennings, 2012).

Suitable crop rotations can increase yields by improving soil health and fertility and reducing erosion (Peterson and Rohweder, 1983; Classen and Kissel, 1984). Canola crops have high residue, (over 3,000 kg ha^{-1}) increasing soil organic matter and reducing soil erosion compared to low residue legume crops like pea and lentil (producing 450-900 kg ha^{-1}) (Gareau and Guy, 1995). Canola plants have strong and deep rooting taproots that can break up plow pans and mining nutrients deeper in the soil profile than the fibrous root systems of cereals or legume crops. Nutrients are preserved rather than being leaching into ground water and water infiltration into and through the soil is improved (Guy and Gareau, 1997; Merril *et al.*, 2002, Weinert *et al*., 2002, Thorup-Kristensen *et al.,* 2003, Vos and Van der Putten, 2004, Malagoli *et al*., 2005, Dean and Weil, 2009). Including a dicot like canola in wheat rotations can be more beneficial than another cereal crop like barley (Peterson and Rohweder, 1983), and yield of wheat following canola is generally higher than following other small grain crops (Kirkegaard *et al*., 1997; Guy and Karow *et al*., 1998). Less internodal damage and take-all (*Gaeumannomyces gramini var. tritici*) symptoms are observed when wheat is rotated with canola (Finnigan, 1994).

2.2.6 Agronomic factors that influence canola

Canola crops should be planted into fertile well drained soils with low potential for weed infestations (Murray *et al*., 1984; Karow and Pumphrey, 1986; Kephart *et al*., 1988; Fribourg *et al*., 1989). Growers should avoid fields with soil residual concentrations of triazine, imidazolinones, most sulfonylureas, and any other herbicides to which canola is susceptible (Karow and Pumphrey, 1986; Kephart *et al*., 1988; Fribourg *et al*., 1989). Canola can be seeded and harvested with conventional small grain cereal equipment.

Some of the factors which impact production and profitability of canola production include the following: (1) cultivar choice; (2) planting date; (3) row spacing; (4) seeding rate; and (5) crop management.

2.2.6.1 Cultivar type

Canola can be grown from spring- and winter-cultivar types. Winter cultivars are planted in the fall, require vernalization, flower the following spring, and are harvested in early summer. Spring cultivars are planted in the spring, do not require vernalization, flower later in the season, and are harvested in late summer. Hybrid and open pollinated cultivars of both spring and winter type are available to growers. Spring canola is generally not as productive as winter canola, where spring canola doesn’t experience crop failure due to freezing temperatures (Karow, 2014).

The highest US acres of spring canola are grown in North Dakota which has a similar climate to Canada allowing growers to utilize well established Canadian cultivars and growing practices. Between 2008 and 2017, the average spring canola yield from the North Dakota State Canola Variety Trial was 1,866 kg ha^{-1} (Kandel *et al.*, 2017).

Dryland winter canola variety performance is regionally dependent in the US. In Kansas, yield of open pollinated winter cultivars averaged 2,242 kg ha^{-1}, and hybrids have markedly higher seed yield, 3,477 kg ha^{-1} (Stamm and Dooley, 2017). In Vermont, winter canola varieties yielded on average 2,078 kg ha^{-1} (Darby *et al.*, 2016).

The dryland agricultural regions of the PNW is one of a few areas of the US where growers can grow either winter- or spring-planted canola. If winter canola is well established in the fall it will generally out-perform spring canola. However, winter canola usually needs to be planted into fallow ground (or irrigated) and hence takes two growing seasons to obtain a crop. Conversely, spring canola is only suited to the higher rainfall regions where continuous cropping is possible. Average winter canola cultivar yield in the

2017 Pacific Northwest winter canola variety trial was 4,383 kg ha^{-1}, and average spring canola yield was only 1,695 kg ha^{-1} (Davis *et al.*, 2017). Irrigated variety trials usually out-yield dryland production.

2.2.6.2 Planting date

Canola planting date is critical because it directly affects seed yield, winter survival, insect infestation, and disease incidence in canola (Hang and Gilliland, 1982; Auld *et al*., 1983; Murray *et al*., 1984; Kephart *et al*., 1988; Fribourg *et al*, 1989; Raymer *et al*., 1990; Thomas *et al*., 1990). The United States Canola Association (USCA) Canola Growers' Manual (Brown *et al.*, 2009) suggests winter canola planting should occur six weeks before the first killing frosts (other than in the southern states). Ideally, at least 45 days of good plant growth should occur before winter conditions (i.e. between 4-6 fully opened leaves in the rosette) (Brown *et al.*, 2009).

Recommended planting dates for winter canola in the Great Plains and Midwest regions change by latitude. In Nebraska, recommended winter canola planting dates should be between August 22nd and September 12th. Recommended dates in Kansas and Missouri are August 26th to September 25th, in Oklahoma and Arkansas, August 20th to September 21st, in Northern Texas, August 20th to September 28th, and in Alabama and Georgia, September 10th to October 25th. Most production winter canola planting in Indiana was between August 25th and September 20th (Christmas, 1996), while in Vermont winter canola oil yields were highest when crops were planted around August 24th (Darby *et al.*, 2013). Optimal planting date for irrigated winter canola in Kansas was between August 30th and September 6th (Holman *et al.*, 2015).

Traditional planting dates for winter canola in Idaho and Washington range between August and early October (Brown *et al.*, 2009). Winter canola should be planted into fallow with higher soil moisture, where yields ranged from 3,800 to 4,670 kg ha^{-1} when planted between July 31st and September 5th, respectively (Murray and Auld, 1986). More recently, earlier planting in the PNW (June and July) has been suggested to obtain better fall plant establishment and to better utilize stored soil moisture which is lost later in the year to evaporation. Planting too late can cause susceptibility to winter kill as smaller seedlings are more sensitive to cold. Similarly, planting too early can cause drought stress are larger plants utilize available stores soil moisture in the absence of timely fall rains (Brown *Pers. Comm.*, 2017).

2.2.6.3 Row spacing

Optimal row spacing in canola varies according to region of production. In Kansas, 20 cm to 40 cm spacing produced good results, and ensured rapid canopy closure, assisting in competition with weeds (Stamm and Ciampitti, 2013). In Australia, wide spacing (30 cm) caused a 9% reduction in yield compared to narrow (15 cm). However, oil content and protein levels were unaffected (Potter *et al.*, 2001).

Canadian row-spacing experiments have shown conflicting evidence. Kondra (1975) showed that 15, 23, and 30 cm had similar yield, but 45 cm row spacing was significantly lower. Clarke *et al.* (1978) observed that narrow (8 cm) row spacing produced over 35% higher yield compared to 15 cm and 23 cm spaced rows. Finally, Morrison *et al.* (1990) observed significantly higher yield in narrow compared to wide row spacing.

Few experiments have examined the optimal row spacing for winter canola production in the PNW, where winter canola can be planted anywhere from 15 to 50 cm. Wider spacing, particularly with high seed cost hybrid cultivars, could be advantageous because lower seeding rates can be used, reducing input costs. Wider rows in direct seed systems can have advantages because there is less chance of high residue disrupting emergence (Brown *et al.*, 2009).

An experiment conducted in eastern Oregon and Washington examined the difference between 15, 30, 60, and 76 cm row spacing (Wysocki and Sirovatka, 2009). Wide rows (60 cm) were successful as long as crops were well established in the fall. Wider row spacing also reduced the energy required to plant, lowering fuel costs, compared to narrow row space planting.

2.2.6.4 Seeding rates

Recommendation seeding rates for winter rapeseed are variable ranging from 4.5 to 13.5 kg ha^{-1} for production in northern Idaho (Moore and Guy, 1997). Some research has shown that winter canola seeding rate does not affect seed yield because of the plasticity of canola crops (Kondra, 1975; Degenhardt and Kondra, 1981; Christensen and Drabble, 1984; Lewis and Knight, 1987; Morrison *et al*., 1990; Brandt, 1994); however, there was inconsistencies between results. Morrison *et al*. (1990) recommended low seeding rates, Chen *et al*. (2005) recommends moderate seeding rates, while Clarke *et al*. (1978) observed increases in yield related to higher seeding rates, although yields do not drop significantly unless there are fewer than 43 plants or greater than 160 plants m^{-2}. Seeding rates that are too low can increase weed infestation and weed competition and seeding rates that are too high can increase lodging because plant stems become especially thin as a result of inter-crop competition (Brown *et al.*, 2009).

In general, early planting requires lower rates and later planting requires higher rates. Direct seeding into wheat stubble may require a 25% increase in seeding rate to account for low emergence resulting from poor seed-soil contact due to large straw residues (Christmas and Hawkins, 1992). Lower seeding rates can be used where weeds are not problematic whereas high rates can be used to assist the competitive ability of canola against weeds (Morrison *et al*., 1990).

Research in the PNW indicates fall seeding rates should be 2-2.5 times higher than optimal plant density because not all seeds become full grown after winter conditions cease (Thill, 2011). A 2014 PNW experiment determined fall planting using 4.5 kg ha^{-1} produced highest see yield, while planting 2.7 and 3.6 kg ha^{-1} has similar yield to seeding as low as 1.8 kg ha^{-1} successfully established (Young *et al.*, 2014). Suggested planting rates in Oregon were 4.5 kg ha^{-1} with earlier planting dates and 9.0 to 13.5 kg ha^{-1} for later planting (Karow, 2014). Recommended seeding rates in Kansas were 5.6 kg ha^{-1} (Holman *et al.*, 2011) and in Washington 7.8 kg ha^{-1} (Sowers *et al.*, 2012).

2.2.6.5 Dual-purpose canola

Canola forage is high in protein and low in fiber and can make a valuable livestock feed. Canola forage crops can be strip grazed, or foliage harvested and ensiled for later feeding. Unlike grass or alfalfa, canola forage cannot be bailed because of its low fiber content (Fraser *et al*., 2001). Unlike other *Brassica* relatives, canola has low glucosinolate levels (Rosa *et al*., 1997). No negative health impacts were detected in sheep grazing canola forage

(Kirkegaard *et al*., 2008; Sprague *et al*., 2014). Canola grown for only seed can be less profitable than tradition small grains. To increase profit margins farmers can utilize canola forage as livestock feed and still have comparably high seed yields (Neely, 2010).

Pioneer work at the University of Idaho has shown that early planted winter canola can be used as forage in the planting year (*Canolage*®), crops thereafter are allowed to over-winter after defoliation and produce a seed crop the following summer, '*dual-purpose canola*' (Neely, 2010; Walsh, 2012). Forage yield of dual-purpose canola ranged from 7 to 8 Mt ha^{-1}, and there was no significant difference between irrigated and dryland biomass quality (Neely, 2010; Walsh, 2012).

Winter canola forage quality is high, and its forage yield is equal to or exceeds dryland alfalfa (Walsh, 2012). Dual-purpose canola has the potential to provide forage harvest without negative effects on seed yield (Dann *et al*., 1977; Epplin *et al*., 2000; Epplin *et al*., 2001; Virgona *et al*., 2006; Kelman and Dove, 2009). There is little added risk of winter damage of grazed canola compared with non-grazed canola, unless grazing delays maturity (Heer, 2006).

Seed yield in foraged canola is affected by planting date. June through August planting dates have higher seed yields than canola planted in May (Walsh, 2012). Two agronomic factors that determine success of dual-purpose canola are early establishment and amount of disease and insect pressures when grazing takes place (Kirkegaard *et al.*, 2007). When investigating the effect seeding rate on forage and seed yield, 6.7 kg ha^{-1} and 9.0 kg ha^{-1} were determined to yield the most forage, however, there were no differences in seed yield (Neely *et al.*, 2015).

The economic feasibility of dual-purpose canola has not been fully examined. Frasen *et al.* (2017) determined that dual-purpose canola yielded significantly less seed than conventionally grown canola. A Washington State University experiment found dual-purpose and conventional canola to return the same cash value in one year, while in another, dual-purpose canola returned \$300 ha^{-1} more than conventional canola (Liewellyn *et al*., 2018).

Producers and researchers need to assess the yield and cash value of canola forage to determine if the forage crop will make up for the potential grain loss. Using canola as a dual-purpose crop could be the most profitable practice i.e. could be a part of the Best Management Practices.

2.2.7 Objectives of this experiment

The aim of this study is to determine the effect of winter canola cultivar, seeding date (with and without forage harvest), row spacing, and seeding rates that optimize production and grower profitability. Specific objectives include:

- To determine whether seed yields are significantly higher if crops are planted early (late July to early August) or if planted late (late August to early September).
- To determine whether it is more economically beneficial to use winter canola as a dual-purpose (forage/seed) crop or only harvest its seed.
- To determine whether seed and forage biomass yields are significantly higher if crops are planted at low (3.4 kg ha^{-1}) or high (5.6 kg ha^{-1}) seeding rates and narrow (25 cm) and wide (50 cm) row spacing.

2.3 Materials and methods

The complete experiment involved growing four winter canola cultivars, planted at two different planting dates, at two row spacing, and two seeding rates, planted at two locations in three years.

2.3.1 Locations, climate, soil

The two locations used in this study were the University of Idaho Parker Farm and Kambitsch Farm. The Parker Farm (785 m elevation) is located 3.2 km east of Moscow, Idaho (46˚73'N, 117˚0'W), with average annual precipitation from 1981-2010 of 69 cm. Soil type is Palouse silt loam. This soil is deep and well drained, formed in loess on hills. It is fine-silty, mixed, superactive, and mesic Pachic Ultic Haploxerolls. Kambitsch Farm (815 m elevation) is located 15.3 km south of Moscow, Idaho (46˚55'N, 116˚92'W), with average annual rainfall from 1980-2010 of 50 cm. Soil type is Naff Palouse silt loam, with fine-silty, mixed, mesic typic Argixerolls.

2.3.1.1 Soil management and pesticides for row space and foliage biomass trials

Soil was managed with a standard tillage regime. After the previous winter wheat crop was harvested the ground was chisel plowed. The following spring glyphosate was applied for general weed control followed by cultivation, fertilizer application, and a final cultivation to incorporate it. Throughout the summer months the ground was rod weed cultivated as needed for weed control. Pre-plant herbicides were not employed because cultivation of fallow and rod weeding.

2.3.1.2 Cultivars

Four winter canola cultivars were selected for this study. ‘Amanda’ [PVP 201100403] and ‘WC15.7.5’ [PVP Pending] are both open pollinated cultivars developed at the University of Idaho. Amanda is susceptible to Group II herbicides while UI.WC.15.7.5 is resistant to Group II herbicides (i.e. imidazolinone, sulfonylurea, etc.). ‘HyClass-125W’ is a Round-up Ready® hybrid cultivar developed by Monsanto Co., marketed by Winfield Seeds. ‘Mercedes’ is a hybrid canola cultivar developed by DL Seeds without herbicide tolerance/resistance developed in Europe and marketed by Rubisco Seeds.

2.3.1.3 Planting dates

Trials were planted at each location early or late, but not necessary on the same day. The planting dates at each site and year are shown in Table 2.1.

2.3.1.4 Seeding rates and row spacing

Two seeding rates and row spacing were examined. High seeding rate was 5.60 kg ha^{-1} and low seeding rate 3.36 kg ha^{-1}. These seeding rates are on the medium to low range of typical seeding rates for winter canola. The USCA Canola Growers’ Manual suggests planting rates that create 107-170 plants m^{-2} when they emerge that create a harvest plant stand of 54-107 plants m^{-2}. High rate was 775,000 seeds ha^{-1}, low seeding rate is 516,600 seeds ha^{-1}. Low seeding rate was 51.4 seeds m^{-2}, and high rate is 77 seeds m^{-2}. Each seeding rate was planted with rows 25 cm and 50 cm apart (i.e. resulting in four rate x row spacing treatments).

2.3.1.5 Variates of row space and foliage biomass trials

Seedling plant stand was recorded two weeks after planting. Seedling stand counts were made from within a 33 cm x 76 cm metal quadrat. Crop establishment rating was recorded four weeks after planting. Establishment was a visual estimation as to how well-established plants were within each plot, based on a 1-9 scale, with 1 = very poorly established, and 9 = very well established. Winter kill ratings were recorded after the winter season by giving plots 1-9 scores. Winter kill ratings were scored by a visual estimation of survival where 1= very poor winter survival and 9= very good winter survival. Days from January 1st to when 50% of the plot was in full flower was recorded. Plant heights for plots were recorded in cm before swathing occurred.

In the foliage biomass trial, biomass samples were taken by cutting all stems 15 cm from the base that were inside of a 33 cm x 150 cm space. Samples were weighed before and after drying to assess forage biomass dry matter using forage material in a 33 cm x 76 cm quadrat.

2.3.1.6 Fertilizer regiment for row space and foliage biomass trials

Soil samples were taken from each location and year prior to planting, and fertility managed according Mahler (2015) recommendation for 1,364 kg ha^{-1} winter canola. Fertilizer applied at the Parker Farm was granular while at Kambitsch farm fertilizer was anhydrous ammonia injected. In 2015 at the Parker Farm 336 kg of 31-10-0-7.5 (numbers correspond to %N-P_2O_5-K_2O-S), 50/50 blend by weight pelletized urea (46-0-0-0) and pelletized ammonium phosphate-sulfate (16-20-0-15), [104 kg of nitrogen, 33 kg of P_2O_5 (phosphorus), and 25 kg of sulfur ha^{-1}], was applied while in 2016 it was 336 kg 31-10-0-6.5 pelletized urea and 16-

20-0-13 ammonium phosphate-sulfate ha^{-1}. At the Kambitsch Farm 111 kg of nitrogen, 11 kg of P_2O_5, 22 kg sulfur ha^{-1} was applied pre-planting using a McGregor Co. "ripper-shooter" applicator as a blend of anhydrous ammonia (82-0-0-0), Thio-Sul® (12-0-0-26), and liquid ammonium phosphate (11-37-0-0) ha^{-1}.

2.3.1.7 Seed and foliage harvest

Eight weeks after planting, half the early planted replicate plots at Kambitsch and Parker farms were harvested for forage (plant biomass). Forage plant biomass was only harvested from half of early planted replicates. All the stems that fit within 33 cm x 76 cm space were cut with hand clippers 15 cm from the soil and placed in paper bags for dry matter calculation. This procedure was guided by laying a quadrat horizontally in the plot so there were three rows were included for narrow rows and so two rows were included for wide rows. A horizontal swath, 33 cm x 150 cm, for plant biomass was weighed in the field to simulate total forage yield. After dry matter sampling was concluded, the stated replicates were mowed to 15 cm from the soil.

At crop maturity, plots were harvested using Wintersteiger Nurserymaster Elite™ (Wintersteiger, Inc.; Salt Lake City, UT) small plot combine. Seed from each plot was harvested into cloth bags and tagged in the field with treatment codes.

2.3.1.8 Post-harvest

Biomass was weighed directly after harvest. Dry matter samples in bags were dried at 43^{o}C for a week and then weighed again to calculate dry matter and moisture content. Seed was dried at 43^{o}C for two days and then weighed. A sub-sample from each plot was taken so oil content analysis could be done on 12 grams of seed. Oil content was analyzed using a Newport MKIIIA Nuclear Magnetic Resonance (NMR) Analyzer (Oxford Instruments Inc.; Concord, MA). The NMR was calibrated with a single reference sample of a known content. Analysis was carried out as described by Howard and Daun (1991).

2.3.2 Experimental design

The experiment design of the complete trial at each site was a strip-strip-plot design with four replicates (i.e. 2 planting dates x 2 row spacing x 2 seeding rates x 4 cultivars x 2 treatments x 4 replicates = 128 plots site^{-1}). Strips were assigned to planting dates and row spacing. Seeding rates and cultivars were randomized as sub-plots within each row spacing. Plots were not assigned to mowing treatments because 2 random replicates were mowed each year. Plots were planted using a five-row flexi coil shank plot drill with press wheels, where each shank planted a double row 10 cm apart and granular fertilizer applied between the pair-rows 3 cm below the seed. Plots were 1.5 m x 4.5 m.

2.3.3 Data analysis

Data was analyzed using a general linear model, Duncan’s multiple range tests (SAS, 2009**).** In the analyses of variance not involving row space, differences between years was tested using the replicates x sites within planting date mean square (Error 1). The effects of 3 years x 2 locations x 2 plantings (10 site-years, with 2 missing site-year combinations) was partitioned into differences between early and late planting (5 site-years of each), and sites within planting dates. The effects of row, row by planting date, row by site within planting date were tested using the row x replicates x sites *w* planting dates mean square (Error 2). The effect of variety, variety x planting date, variety x row, variety x planting date x row, rate, rate x planting date, rate x row, rate x variety, rate x planting date x row, rate x row x variety, and rate x planting date x variety, were tested for significance using the general, pooled error (Error 3).

In the analyses of variance involving forage plant biomass, differences between years was tested using the replicates _w_ sites mean square (Error 1). The effects of row and row x year were tested using the year x replicates x row _w_ sites mean square (Error 2). The effect of mow, year x mow, row x mow, year x row x mow interactions were tested using the year x replicates x mow x row _w_ sites mean square (Error 3). The effects of variety, year x variety, variety x row, year x variety x row, variety x mow, year x variety x mow, variety x row x mow, year x variety x row x mow, rate, variety x rate, year x rate, row x rate, rate x mow, year x variety x rate, variety x row x rate, year x row x rate, variety x rate x mow, year x rate x mow, row x rate x mow, row x rate x mow, and year x variety x row x rate were tested using the general, pooled error (Error 4).

2.4 Results and Discussion

Statistical significance of means squares from the analyses of variance of seedling plant stand, crop establishment, winter kill, days to 50% flower bloom, plant height after flower end, and seed yield of four cultivars, planted at two sites, over two years, at two dates, with two row spacing, two seeding rates, and four replicates are presented in Table 2.2. Planting date had a significant impact on all traits examined, except seed yield and crop establishment. Similarly, sites *w* planting date interactions were significant for all traits. Row spacing impacted seeding plant stands and crop establishment but did not affect other traits measured. Cultivars differed in plant stand, plant height, and flowering. In general, most of the two-way and all higher order interactions were not significant.

2.4.1 Seedling plant stand

Seedling plant stands were significantly higher when planted later in the fall (Table 2.3). This might have been expected because early planting resulted in larger plants creating greater inter-plant competition, and with limited water availability, this in agreement with the recommendation of higher seeding rates for later planting dates (Karow, 2014)**.** Seedling plant stands were significantly higher in wider rows compared to narrower rows. This also might be explained because there is more space between rows allowing plants' root systems to spread without being restricted by other plants and there is less competition for light and water because the rows are planted east to west. There was no interaction between planting date and row spacing.

Seedling stands were lowest for Mercedes (56.4 plants m^{-2}) and WC15.7.5 (59.2 plants m^{-2}), while plant stands of Amanda and HyC125W were significantly higher (Table 2.4). It should be noted that seeding rates were based on weight of seed planted rather than actual number of seeds planted, and although seed size was not recorded, cultivar differences could have been confounded with seed size. If fewer seeds are planted, because of greater seed size, potential seedling stand is inherently lower than plots where more seeds, because of lesser seed size, were planted.

2.4.2 Crop establishment

Planting date had no effect on visual crop establishment (Table 2.5) and good crop stands were possible for early and later planting. However, visual crop stand establishment was significantly better with narrow rows compared to wide rows, perhaps simply an artifact of visual evaluation where wide rows had greater bare ground compared to narrower rows. So, it is possible that narrow rows being planted closer had the appearance of being 'better' established. In any case, both row spacing resulted in good plant stands. The interaction between row space and planting date was significant in the analysis of variance, but there was little change in relative ranking between treatments, although there was greater (scalar) difference in crop establishment at wider spacing compared to narrow row spacing. In general, crop establishment was good for all cultivars, although crop establishment of Mercedes was significantly lower than the other 3 cultivars (Table 2.6).

2.4.3 Winter kill rating

Winter canola planted early showed significantly greater winter kill damage (5.5 rating) compared to winter kill rating of late-planted winter canola (6.5 rating) (Table 2.7). However, it should be noted that winter kill damage was never severe enough to cause crop loss in any of the site-years. No other significant winter kill effects were observed on other treatments examined. It is possible that older plants being larger, have faster metabolism, and require more energy to maintain health and have a longer acclimation period, making them more susceptible to low temperatures compared to smaller and younger plants. The Canola Growers' Manual suggests planting 45 days before the first frost, but that earlier planting can contribute to increased winter kill susceptibility (Brown *et al.*, 2009).

2.4.4 Days from January 1st to 50% flower bloom

Winter canola flowering dates were independent of planting date, row spacing and seeding rates. However, Amanda and HyC125W reached 50% flower bloom later (129 days after January 1st) than WC15.7.5 (130 d), while Mercedes flowered significantly earlier at 123 days after January 1st (Table 2.8).

2.4.5 Plant height

Winter canola planted early was significantly shorter after flowering (157 cm) compared to later planted crops (168 cm) (Table 2.9). Planting later resulted in higher seedling plant stands compared to earlier planting, resulting in greater inter-plant competition and etiolated plants due to increased competition. Taller plants under high density could result in thinner stems, potentially leading to greater lodging. However, no significant lodging was observed in any of these trials. The tallest cultivar was Mercedes, which was 17 cm taller than WC15.7.5 and the shortest cultivars were Amanda and HyC125W, both at 157 cm. There was a statistically significant interaction between cultivars and planting date for plant height, although this interaction appeared scalar in that the relative rankings of the cultivar heights was the same irrespective of planting date. Mercedes being tallest and Amanda plus HyC125W being shortest.

2.4.6 Seed Yield

Seed yield of canola averaged over all site-years was not affected by row spacing or planting date (Table 2.10) and all row spacing and planting dates produced high average seed yield (3,584 kg ha^{-1}). Therefore, results differed from those previous where narrow rows were higher yielding compared to wide rows (Kondra, 1975; Clarke *et al.*, 1978; Morrison *et al.*, 1990), but rather confirms that different row spacing produce high seed yield in the PNW (Brown *et al.*, 2009; Wysocki and Sirovatka, 2009).

Seed yield was significantly different for the cultivars examined, but there was no cultivar x planting date (Table 2.11), cultivar x row spacing (Table 2.12), nor cultivar x seeding rate (Table 2.13) interactions. The highest yielding cultivar was Mercedes at 3,943 kg ha^{-1}, while HyC125W was the lowest yielding cultivar at 3,343 kg ha^{-1}. Amanda and WC15.7.5 produced intermediate seed yield with Amanda out-yielding WC15.7.5 by 64 kg ha^{-1}. Mercedes is known to be high yielding from previous studies but often the yield advantage does not compensate for the high seed costs. Amanda and WC15.7.5 were developed by the University of Idaho showing that public funded variety development can compete with privatized development. This is the case because fewer funds are needed to run variety development research. Successful cultivars are developed with less overhead costs so seed for planting is cheaper. HyC125W is a hybrid cultivar marketed by CROPLAN Genetics and being lowest yielding indicates that hybrid cultivars are not always associated with increased seed yield over open pollinated cultivars and, in this case, would not justify the high cost of hybrid seed.

2.4.7 Economics

Basic economic analyses were carried out to determine gross return to growers. Included in the analyses are seed cost and whether growers include value for forage harvested from early planting. All other growing and depreciation costs are ignored. In the economic analyses, it is assumed that: Commodity canola value is set at \$0.41 kg^{-1}; forage value is set at \$109 Mt^{-1}; seed costs for Mercedes at \$41.3 kg^{-1}, HyC125W at \$35.4 kg^{-1}, and Amanda and WC15.7.5 at \$7.7 kg^{-1}.

2.4.7.1 Row space

The top two seed yielding cultivars were Amanda and Mercedes so further cost analysis was conducted only on these. The highest gross return resulted for planting later, irrespective of cultivar choice. Mercedes produced the highest seed yield, however, seed costs of Mercedes (\$41.3 kg^{-1}) was markedly higher than these for Amanda (\$7.7 kg^{-1}) and need to be considered. The top three highest gross return was obtained by growing Mercedes, grown: (1) \$1,889 ha^{-1}, planted late on wide row spacing at low seeding rate; (2) \$1,885 ha^{-1}, planted late under wide row spacing and high seeding rate; and (3) \$1,820 ha^{-1}, planted late under narrow row spacing and low seeding rate, respectively (Table 2.14). Mercedes gross return more than compensated for the higher seed costs for this cultivar. The highest gross return from the cultivar Amanda also resulted from later planting, but Amanda did relatively better under narrow row spacing, with best gross crop return being \$1,701 ha^{-1}, from planting late with narrow row spacing and a high seeding rate.

2.4.7.2 Forage yield

Statistical significance of means squares from the analyses of variance of seed yield and forage biomass of four cultivars, planted at two sites, over two years, planted early with forage harvested in the fall or planted early with no forage harvest; with two row spacing, two seeding rates, and two replicates are presented in Table 2.15. Site effects were highly significant for seed and forage yield. Row spacing significantly influenced forage yield, with higher forage yield with wide row spacing (Table 2.16); and seeding rate influenced seed yield (Table 2.17), with higher seed yield from lower seeding rates. However, all two-way and higher order interactions were not significant.

Averaged over early planted mowed and not mowed plots, seed yield Mercedes, Amanda and WC15.7.5 were not significantly different (Table 2.18), but seed yield of HyC125W was significantly lower than Mercedes.

Forage value added between \$786 to \$1,047 ha^{-1} to the overall crop value (Table 2.20) yet forage harvest had little or no effect of seed yield (Table 2.19). When seed yield and forage yield values are combined, gross return was greater than when only seed was harvested. The highest grower return of forage and seed was from cultivar Amanda, planted on wide row spacing with high seeding rate (\$3,012 ha^{-1}). The greatest gross return from seed and forage harvest differed for each cultivar; highest gross return for WC15.7.5 (\$2,871 ha^{-1}) also was from wide row with spacing high seeding rate; for HyC125W (\$2,668 ha^{-1}) planted on wide row spacing with low seeding rate; and for Mercedes (\$2,696 ha^{-1}) planted on narrow row spacing with low seeding rate. Overall, optimized economic returns require different treatments for each cultivar and whether the crop is grown for seed alone or dual purpose (forage and seed).

2.5 Conclusions and recommendations

Winter canola seed yield is affected by genetic and agronomic factors: cultivar choice, planting date, row spacing, seeding rate, and whether forage is harvested (Wysocki and Sirovatka, 2009; Neely, 2010; Reed, 2015).

Planting date, row spacing, and seeding rate had little or no impact on seed yield potential, and high winter canola seed yield was obtained from all combinations of treatments examined. It should be noted that early planting might be advantageous in some years and locations where summer fallow soil moisture is limiting, and it can often be easier to obtain good crop establishment when planting early.

Mercedes produced higher seed yield and greater gross return from seed harvest compared to the other three cultivars, while lowest seed yield and profitability was from the hybrid cultivar HyC125W. However, all four cultivars examined produced good seed yields. The Average 2017 PNW Winter Canola Variety Trial Results seed yield was 4,383 kg ha^{-1} (Davis *et al.*, 2017). The average seed yield in this experiment was 3,608 kg ha^{-1}.

Gross return from winter canola planted on fallow ground can be markedly increased by harvesting forage in the fall plus seed the following summer (Dual purpose winter canola), as first demonstrated by Neely (2010) and Walsh (2012). Forage harvest can increase gross return by over $1,000 ha^{-1}. Maximum gross return from dual purpose winter canola is achieved using different treatments than canola grown for seed only, beyond their inherent differences of planting date and mowing treatment (i.e. cultivar, seeding rate, row spacing).

In conclusion, when growing winter canola for seed only, plant Mercedes late, with wide row spacing and low seeding rates. However, when growing dual purpose winter canola for seed and forage, then plant Amanda early with wide row spacing and high seeding rate to optimize gross return on the crop.

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Table 2.1 Planting dates of winter canola planted at 2 sites, at 2 planting dates, over 3 years including both the seed only and forage biomass experiments.

	Parker Farm		Kambitsch Farm	
Year	Early Planting	Late Planting	Early Planting	Late Planting
2014	July 17th	August 15th †	July 15th	August 18th
2015	July 21st	August 25th	July 20th †	August 25th
2016	July 21st	September 8th	August 1st	September 9th

† It should be noted that soil moisture at Parker Farm Late Planting in fall of 2014 and Kambitsch Farm Early Planting in 2015 was very low and these trials did not establish sufficiently to allow them to be included in the experiment.

Table 2.2 Significance of means squares from the analysis of variance of seedling stand, crop establishment, crop winter kill, days to 50% flower bloom, plant height after flowering end, and seed yield of four cultivars, planted on two dates at two sites, over two years, with two row spacing, two seeding rates, and four replicates from the row space experiment.

Variate Source	d.f.[a]	Stand†	Estab.	Win. Kill	Flower	Height	Yield
Date	1	***	ns	***	*	***	ns
Site *w* date	9	***	***	***	***	***	***
Error (1)§	28	***	***	***	***	***	ns
Row	1	***	**	ns	ns	ns	ns
Row x date	1	*	**	ns	ns	ns	ns
Row x site *w* date	9	***	**	ns	ns	ns	*
Error (2)	28	ns	ns	***	ns	ns	ns
Variety	3	**	ns	ns	***	***	ns
Variety x date	3	ns	ns	ns	***	***	ns
Variety x site *w* date	24	*	ns	*	***	***	*
Row x variety	3	ns	ns	ns	ns	ns	ns
Row x variety x date	3	ns	ns	ns	ns	ns	ns
Row x variety x site *w* date	24	ns	ns	ns	ns	ns	ns
Rate	1	***	***	ns	ns	ns	ns
Rate x date	1	ns	ns	ns	ns	ns	ns
Rate x site *w* date	9	*	ns	ns	ns	ns	ns
Row x rate	1	ns	ns	ns	ns	ns	ns
Variety x rate	3	ns	ns	ns	ns	ns	ns
Row x rate x date	1	ns	ns	ns	ns	ns	ns
Row x variety x rate	3	ns	ns	ns	ns	ns	ns
Variety x rate x date	3	ns	*	ns	ns	ns	ns
Row x rate x site *w* date	9	ns	ns	ns	ns	ns	ns
Variety x rate x site *w* date	25	ns	ns	ns	ns	ns	ns
Row x variety x rate x site *w* date	28	ns	ns	ns	ns	ns	ns

n.s. = not formally significant at the 5% level of probability; * = 0.01<P<0.05; ** = 0.001<P<0.01; *** = P<0.001. [a] degrees of freedom;

† Stand = seedling plant stand; Estab = visual evaluation of fall crop establishment; Win. Kill = winter survival rating; Flower = estimated days to 50% flowering; Height = average plot plant height; Yield = adjusted seed yield ha^{-1} of plot.

§ Error(1) = Rep x site *w* date; Error (2) = Rep x row x site *w* date.

Table 2.3 Seedling plant stands for winter canola planted at two different planting dates (early and late) and two different row spacing (25 cm and 50 cm). Data presented are averaged over 10 site-years, 4 cultivars, and 2 seeding rates.

	Row spacing		
Planting Date	25 cm	50 cm	Mean
	------------------- Plants m$^{-2†}$	----------------	
Early	44.4	52.0	48.2 ^{b}
Late	65.2	84.0	74.6 ^{a}
Mean	54.8 ^{b}	68.0 ^{a}	61.4

[†] = Count of plants m^{-2} at the 4-6 leaf stage.

Means within rows and columns with different superscript letters are significantly different (0.01<P<0.05).

LSD 5% for Row = 5.3; LSD 5% for Planting date = 10.1.

Table 2.4 Seedling plant stands for four varieties of winter canola planted at two different dates (early and late). Data presented are averaged over 10 site-years, 2 row spacing, and 2 seeding rates.

	Planting Date		
Cultivars	Early	Late	Mean
	-------------------- Plants m$^{-2†}$	------------------	
Amanda	51.5	80.1	65.8 ^{a}
HyC125W	52.1	78.1	65.1 ^{a}
Mercedes	45.1	66.6	55.9 ^{b}
WC15.7.5	44.2	73.7	59.0 ^{ab}
Mean	48.2 ^{b}	74.6 ^{a}	

† = Count of plants m^{-2} at the 4-6 leaf stage

Means within rows and columns with different superscript letters are significantly different (0.01<P<0.05).

LSD 5% for planting date = 10.1; LSD 5% for Variety = 6.9.

Table 2.5 Crop establishment ratings for winter canola under 2 row spacing (25 cm and 50 cm) and planted at two different dates. Data presented over 10 site-years, 4 cultivars, and 2 seeding rates.

	Row Spacing		
Plant Date	25 cm	50 cm	Mean
	-------------------1 to 9 scale†---------------------		
Early	7.0	6.5	6.7
Late	6.9	6.9	6.9
mean	7.0 ^{a}	6.6 ^{b}	

† = Visual assessment of how well plants had established prior to bolting where 1 = very poor establishment; 9 = very good establishment.

Means within rows and columns with different superscript letters are significantly different (0.01<P<0.05).

LSD 5% for Row Spacing = 0.34. LSD 5% for Planting date = 0.53.

Table 2.6 Crop establishment ratings for four winter canola varieties planted at two different dates (early and late) and at two different seeding rates (3.4 and 5.6 kg ha^{-1}). Data presented are averaged over 10 years-sites and 2 row spacing.

	Planting Date				
	Early		Late		
Seeding Rate	3.4	5.6	3.4	5.6	Means
Cultivars	----------------------------------1 to 9 scale†-----------------------------				
Amanda	6.4	7.3	7.3	7.4	7.0 ^{a}
HyC125W	6.5	7.2	6.2	6.6	6.7 ^{a}
Mercedes	5.5	5.9	6.8	6.5	6.1 ^{b}
WC15.7.5	6.7	7.2	6.4	7.4	6.9 ^{a}
Means	6.3	6.9	6.7	7.0	6.7
Seeding Rate	3.4	5.6			
Means	6.5 ^{b}	7.0 ^{a}			

† = Visual assessment of how well plants had established prior to bolting where 1= very poor establishment; 9 = very good establishment.

Means within rows and columns with different superscript letters are significantly different (0.01<P<0.05).

LSD 5% for planting time = 0.53; LSD 5% for rate = 0.24; LSD 5% for variety = 0.36.

Table 2.7 Winter kill ratings for winter canola planted at two different row spacing (25 cm and 50 cm) and two different seeding rates (3.4 and 5.6 kg ha-1) and two different dates (early and late). Data presented are averaged over 10 years-sites and 4 cultivars.

	Planting Date				
	Early		Late		
Seeding Rate	3.4	5.6	3.4	5.6	Mean
Row Spacing	---------------------------------1 to 9 scale†--------------------------------				
25 cm	5.4	5.4	6.6	6.4	5.9
50 cm	5.7	5.4	6.4	6.8	6.0
Mean	5.5	5.4	6.5	6.6	

† = Visual assessment of winter kill ratings where 1 = very poor winter survival; 9 = very good winter survival.

Means within rows and columns with different superscript letters are significantly different ($0.01<P<0.05$).

LSD 5% for time = 0.66; LSD 5% for rate 0.24; LSD 5% for row 0.47.

Table 2.8 Days from January 1st to 50% flower bloom for four winter canola varieties at two different planting dates. Data presented are averaged over 10 years-sites, 2 row spacing, and 2 seeding rates.

	Planting Date		
Cultivars	Early	Late	Means
	--------------Days from January 1st †----------------		
Amanda	130	129	129 ^{ab}
HyC125W	129	129	129 ^{b}
Mercedes	122	124	123 ^{c}
WC15.7.5	130	131	130 ^{a}
Means	128	128	

† = Days from January 1st to 50% flower bloom.
Means within rows and columns with different superscript letters are significantly different ($0.01<P<0.05$).

LSD 5% for Time = 1.2, LSD 5% for variety = 1.1.

Table 2.9 Plant height after flower ending for four winter canola varieties planted at two different planting dates (early and late). Data presented over 10 site-years, 2 row spacing, and 2 seeding rates.

	Planting Date		
Cultivar	Early	Late	Means
	---------------Plant Height cm†------------		
Amanda	152	162	157 ^{c}
HyC125W	150	165	157 ^{c}
Mercedes	176	179	178 ^{a}
WC15.7.5	156	166	161 ^{b}
Means	157 ^{b}	168 ^{a}	

† = Plant height in cm recorded after flower ending.
Means within rows and columns with different superscript letters are significantly different (0.01<P<0.05).
LSD 5% for time = 3.3, LSD 5% for variety = 2.4.

Table 2.10 Seed yield of winter canola planted at two different planting dates (early and late) and two different row spacing (25 cm and 50 cm). Data presented are averaged over 10 years-sites, 4 cultivars, and 2 seeding rates.

	Planting Date		
Row Spacing	Early	Late	Means
	--------------------kg ha^{-1}†-----------------------		
25 cm	2,981	4,140	3,601
50 cm	2,793	4,221	3,555
Means	2,887 ^{b}	4,180 ^{a}	

† = Seed yield after air drying (kg ha^{-1}).
Means within rows and columns with different superscript letters are significantly different (0.01<P<0.05).
LSD 5% for Time = 157; LSD 5% for Row = 137.

Table 2.11 Seed yield of four varieties of winter canola planted at two different planting dates. Data presented are averaged over 10 years-sites, 2 row spacing, and 2 seeding rates.

	Planting Date		
Cultivars	Early	Late	Means
	---------------------kg ha^{-1}†----------------------		
Amanda	2,854	4,015	3,465 ^{b}
HyC125W	2,588	3,843	3,248 ^{c}
Mercedes	3,527	4,989	4,363 ^{a}
WC15.7.5	3,457	3,625	3,442 ^{b}
Means	2,887 ^{b}	4,180 ^{a}	

† = Seed yield after air drying (kg ha^{-1}).
Means within rows and columns with different superscript letters are significantly different (0.01<P<0.05).

LSD 5% for Time = 157; LSD 5% for Variety = 182.

Table 2.12 Seed yield of four varieties of winter canola planted at two different row spacing (25 cm and 50 cm). Data presented are averaged over 10 years-sites, 2 planting dates, and 2 seeding rates.

	Row Spacing		
Cultivars	25 cm	50 cm	Means
	--------------------kg ha^{-1}†---------------------		
Amanda	3,577	3,353	3,465 ^{b}
HyC125W	3,228	3,269	3,248 ^{c}
Mercedes	4,351	4,374	4,363 ^{a}
WC15.7.5	3,445	3,439	3,442 ^{b}
Means	3,601	3,555	

† = Seed yield after air drying (kg ha^{-1}).
Means within rows and columns with different superscript letters are significantly different (0.01<P<0.05).
LSD 5% for Variety = 182; LSD 5% for Row = 137.

Table 2.13 Seed yield of four varieties of winter canola planted at two different planting rates (3.4 and 5.6 kg ha^{-1}). Data presented are averaged over 10 site-years, 2 planting dates, and 2 row spacing.

	Seeding Rate		
Cultivars	3.4	5.6	Means
	--------------------kg ha^{-1}†	---------------------	
Amanda	3,350	3,581	3,465 ^{b}
HyC125W	3,234	3,262	3,248 ^{c}
Mercedes	4,303	4,422	4,363 ^{a}
WC15.7.5	3,486	3,398	3,442 ^{b}
Means	3,593	3,666	

† = Seed yield after air drying (kg ha^{-1}).

Means within rows and columns with different superscript letters are significantly different ($0.01<P<0.05$).

LSD 5% for Variety = 182; LSD 5% for Rate = 127.

Table 2.14 Gross grower return after seed costs of Mercedes and Amanda winter canola planted early and late at two seeding rates and two row spacing.

Cultivar		Row Spacing	Seed Rate	Seed Cost‡	Seed Yield	Seed Value†	Gross Return	Gross Return Rank
				- \$ kg^{-1} -	- kg ha^{-1} -	---------	\$ ha^{-1}	---------
Mercedes	Early	Narrow	High	268	3,881	1,591	1,323	9
			Low	178	3,541	1,452	1,274	10
		Wide	High	268	3,362	1,378	1,110	15
			Low	178	3,323	1,362	1,185	12
	Late	Narrow	High	268	4,792	1,965	1,696	5
			Low	178	4,872	1,997	1,820	3
		Wide	High	268	5,253	2,154	1,885	2
			Low	**178**	**5,042**	**2,067**	**1,889**	**1**
Amanda	Early	Narrow	High	50	2,965	1,216	1,166	13
			Low	33	2,806	1,151	1,117	14
		Wide	High	50	3,035	1,244	1,194	11
			Low	33	2,611	1,071	1,037	16
	Late	**Narrow**	**High**	**50**	**4,271**	**1,751**	**1,701**	**4**
			Low	33	4,130	1,693	1,660	6
		Wide	High	50	3,937	1,614	1,564	7
			Low	33	3,725	1,527	1,494	8

‡ seed cost based on OP seed = \$7.07 kg^{-1}; hybrid seed = \$36.31 kg^{-1}.

† Based on Pacific Coast Canola (Viterra) grower price October 1st, 2018 value of \$0.41 kg^{-1}.

Bold shows highest gross return for each cultivar based on seed harvest only.

Table 2.15 Significance of means squares from the analysis of variance of seed yield and foliage yield of four cultivars (CV), planted early only at two sites (Sites), over two years (Year), with two row spacing (Row), two seeding rates (Rate), and either mowed or not mowed (Mow) in the fall and two replicates from the forage biomass experiment.

Variate Source	d.f.[a]	Seed Yield[†]	Forage Yield
Site	1	***	***
Error (1)[§]	2	ns	ns
Row	1	ns	***
Year x Row	1	*	***
Error (2)	2	ns	***
Mow	1	ns	***
Year x Mow	1	ns	ns
Row x Mow	1	ns	ns
Year x Row x Mow	1	ns	***
Error (3)	4	ns	ns
CV	3	*	ns
Year x CV	3	ns	*
CV x Row	3	ns	ns
Year x CV x Row	3	ns	ns
CV x Mow	3	ns	ns
Year x CV x Mow	3	*	ns
CV x Row x Mow	3	ns	ns
Year x CV x Row x Mow	3	ns	ns
Rate	1	***	ns
CV x Rate	3	ns	ns
Year x Rate	1	ns	ns
Row x Rate	1	ns	ns
Rate x Mow	1	ns	ns
Year x CV x Rate	3	ns	ns
CV x Row x Rate	3	ns	ns
Year x Row x Rate	1	ns	ns
CV x Rate x Mow	3	ns	ns
Year x Rate x Mow	1	ns	ns
Row x Rate x Mow	1	ns	ns
Year x CV x Row x Rate	3	ns	ns

n.s. = not formally significant at the 5% probability level; * = $0.01<P<0.05$; ** = $0.001<P<0.01$; *** = $P<0.001$.

[a] Degrees of Freedom.

† Yield = adjusted seed yield ha^{-1}; Forage yield = forage biomass (ha^{-1}) harvested in fall after planting.

§ Error (1) = Rep *w* sites; Error (2) = Rep x Year x row *w* site; Error (3) = Rep x Year x row x mow *w* site;

Table 2.16 Forage biomass of two different row spacing (25 cm and 50 cm). Data presented are averaged over 4 cultivars, 2 seeding rates, 2 mow treatments, and 2 site-years.

Row Space	
25 cm	50 cm
--------------kg ha^{-1}[†]------------	
5,987 [b]	7,046 [a]

Means within rows and columns with different superscript letters are significantly different (0.01<P<0.05). LSD 5% for Row Space = 855.

Table 2.17 Seed yield of winter canola planted with two different seeding rates (3.4 kg ha^{-1} and 5.6 kg ha^{-1}). Data presented are averaged over 4 cultivars, 2 row spacing, 2 mow treatments, and 2 site-years.

Seeding Rate	
3.4 kg ha^{-1}	5.6 kg ha^{-1}
--------------kg ha^{-1}[†]------------	
4,360 [a]	4,024 [b]

Table 2.18 Seed yield of four different winter canola cultivars. Data Presented are averaged over 2 row spacing, 2 seeding rate, 2 mow treatment and 2 site-years.

Cultivar			
Amanda	HyC125W	Mercedes	WC15.7.5
-------------------------------kg ha^{-1}†		------------------------------------	
4,152 ^{ab}	3,995 ^{b}	4,452 ^{a}	4,168 ^{ab}

† = Seed yield (kg ha^{-1}).
Means within rows and columns with different superscript letters are significantly different (0.01<P<0.05).
LSD 5% for Variety = 323.

Table 2.19 Seed yield of two mow treatments. Data Presented are averaged over 4 cultivars, 2 row spacing, 2 seeding rates, 2 mow treatments and 2 site-years.

Mow Treatment	
Mow	No-Mow
--------- kg ha^{-1}†	----------
4,087	4,296

Table 2.20 Gross grower return after seed costs and adjustment to account optional forage harvest and sales of Mercedes and Amanda winter canola planted early and late at two seeding rates and two row spacing. Note that forage is only harvested from the early planting dates.

Cultivar		Row Spacing	Seed	Seed Cost †	Forage value‡	Seed value††	Gross Return	Return Rank
				----------------------	$\$ \text{ ha}^{-1}$	----------------------		
Mercedes	**Mowed**	**Narrow**	High	269	911	1,925	2,567	11
			Low	**178**	**842**	**2,032**	**2,696**	**5**
		Wide	High	269	928	1,782	2,441	13
			Low	178	1047	1,763	2,632	7
	No Mow	*Narrow*	High	269	0	2,313	2,044	20
			Low	*178*	*0*	*1,867*	*1,689*	*30*
		Wide	High	269	0	2,115	1,846	27
			Low	178	0	2,088	1,910	23
Amanda	**Mowed**	Narrow	High	46	817	2,081	2,852	3
			Low	30	786	1,603	2,359	14
		Wide	**High**	**46**	**967**	**2,091**	**3,012**	**1**
			Low	30	1014	1,832	2,816	4
	No Mow	*Narrow*	High	46	0	1,967	1,921	22
			Low	*30*	*0*	*1,681*	*1,651*	*31*
		Wide	High	46	0	1,976	1,930	21
			Low	30	0	1,808	1,778	28
HyC125W	**Mowed**	Narrow	High	211	856	1,641	2,286	15
			Low	138	835	1,500	2,198	16
		Wide	High	211	951	1,815	2,555	12
			Low	**138**	**935**	**1,871**	**2,668**	**6**
	No Mow	*Narrow*	*High*	*211*	*0*	*1,941*	*1,730*	*29*
			Low	138	0	1,989	1,851	25
		Wide	High	211	0	2,059	1,848	26
			Low	138	0	1,774	1,636	32
WC15.7.5	**Mowed**	Narrow	High	46	788	1,831	2,573	10
			Low	31	868	1,771	2,608	8
		Wide	**High**	**46**	**975**	**1,942**	**2,871**	**2**
			Low	31	912	1,698	2,580	9
	No Mow	Narrow	High	46	0	2,133	2,087	17
			Low	31	0	2,107	2,077	18
		Wide	*High*	*46*	*0*	*1,916*	*1,870*	*24*
			Low	31	0	2,075	2,045	19

‡ seed cost based on OP seed = \$7.07 kg^{-1}; hybrid seed = \$36.31 kg^{-1}.

† based on alfalfa equivalent \$120 ton^{-1} Capital Press, August 2018.

†† Based on Pacific Coast Canola (Viterra) grower price October 1st, 2018 value of \$0.41 kg^{-1}.

Bold shows highest gross return for forage and seed harvest; *italics* shows highest gross return for seed only harvest.

Chapter 3: Effect of spring and winter rotation crops following winter wheat productivity and profitability in two-year crop rotations in the Northern Idaho

3.1 Abstract

Cereal grains occupy 80% of the dryland acreage in the Pacific Northwest, and there are few profitable alternative crop options to include in rotations. The greatest issue facing cereal production in the PNW is the control of grass weeds because: (1) both crop and weed have similar biochemical pathways meaning chemical control options are limited; and (2) development of herbicide tolerant grass weeds. Alternative crops break disease cycles, help control weeds, and diversify production. The best alternative rotation crops with cereals are broadleaf species. Canola has shown good adaptability to the area and has the potential to be a profitable crop in the Pacific Northwest. Traditional rotation crops in the region have included legume crops such as garbanzo bean, lentil and pea. Cereals and legume crops are both shallow rooted with fibrous root systems compared to the strong deep-rooted taproot of canola which can benefit soil structure management. However, the effects of wheat-canola rotations need to be quantified to determine the impact, long-term sustainability, and profitability of this cropping system. Two multiple year field studies were grown to evaluate the effects of spring and winter rotation crops on the performance of subsequent winter wheat crops. At Parker Farm, the winter rotation, winter canola, AWP, winter wheat plots and fallow were treatments in the first year, while at Kambitsch Farm, the spring rotation, spring barley, canola, pea, and wheat plots were planted in the first year. Seed from all year-1 crops plots were harvested at maturity and air dried to uniform moisture before being

weighed. After harvest, soil samples were taken and sent to be analyzed for nutrient content and soil moisture. Two weeks after crop harvest water infiltration was determined. In fall following the year-1 crops, winter wheat was planted over both trial areas. At maturity, the wheat was harvested according to the previous year's crop and weighed. Spring wheat and spring barley produced significantly higher seed yield compared to spring canola, and spring pea had the lowest spring crop yield. Commodity crop prices at harvest resulted in the greatest spring crop gross returns from spring canola (\$1,092 ha^{-1}), followed by spring wheat (\$882 ha^{-1}) and barley (\$780 ha^{-1}), with lowest returns from pea. Winter wheat yield following spring wheat (918 kg ha^{-1}) and spring canola (857 kg ha^{-1}) were not significantly different. Winter wheat following spring wheat yield was significantly higher than winter wheat following spring barley (796 kg ha^{-1}). The highest grower gross return over two years crop potation was from spring canola-winter wheat (\$1,949 ha^{-1}), followed by spring wheat-winter wheat (\$1,800 ha^{-1}), and lowest grower gross return from pea-winter wheat (\$1,229 ha^{-1}) rotations. Winter wheat yield (6,881 kg ha^{-1}) was almost double that obtained from winter canola (3,841 kg ha^{-1}) in the winter rotation study. However, commodity prices at harvest resulted in significantly higher gross returns from winter canola (\$1,859 ha^{-1}) compared to winter wheat (\$1,322 ha^{-1}). In general, winter wheat following winter crops had higher yield and greater 2-year returns compared to spring crop-winter wheat. Winter wheat following AWP (\$1,350 ha^{-1}) and winter canola (\$1,293 ha^{-1}) was significantly higher than winter wheat following winter wheat (\$1,075 ha^{-1}) or fallow (\$1,121 ha^{-1}). The highest two-year gross return from winter rotations was winter canola-winter wheat (\$3,152 ha^{-1}), followed by winter wheat-winter wheat (\$2,397 ha^{-1}), AWP-winter wheat (\$1,589 ha^{-1}), and the lowest grower return from fallow-winter wheat (\$1,121 ha^{-1}). Suitable crop rations are critical in sustainable crop production systems, and PNW growers need to consider the potential gross return on crops in rotation over multiple years when deciding on which crops to grow. Different rotation crops had greater or lesser effects preceding winter wheat. Canola did indeed prove to be an excellent rotation crop when planted before winter wheat, winter canola more so than spring canola. One of the beneficial effects of including canola into cereal crop rotations is better fall water infiltration, most likely related to the different and more aggressive taproot system of canola crops.

3.2 Introduction

3.2.1 PNW agriculture

Humid winters and hot dry summers characterize the PNW as a Mediterranean climate (Skidmore and Woodruff, 1968), making the dryland region highly suitable for small cereal grain production. The PNW is the top dryland small grain cereal grain production region of the US, and among the highest wheat (*Tritcum aestivum*) yielding regions of the world. In 2017, the US national average wheat yield was 3,376 kg ha^{-1} (USDA, 2018), while in Idaho average wheat yield was 5,501 kg ha^{-1} (USDA, NASS, 2017). Including non-cereal crops is limited because of agronomic and economic challenges (Yorgey and Kruger, 2017).

In many regions of the world, wheat is a staple caloric source (Smith, 1995; Karvy and Comtrade, 2010). Since the 1800’s, PNW farming systems have relied almost entirely on tillage-based wheat-fallow systems. Low rainfall areas which comprise over half of PNW dryland acreage where fallow is common due to low summer rainfall, and hence crops are produced every other year (Schillinger *et al*., 2006). Regions receiving 45 cm or more annual rainfall do not require a fallow period, thus, rotate winter wheat and spring pulse in an annual cropping system (Granatstein, 1992). Winter wheat has higher yield potential than spring wheat and greater economic returns compared to available alternative crops in the region (Guy and Lauver, 2006). Winter wheat has more time to access winter soil moisture. Flowering and grain fill periods are less likely to be affected by high summer temperatures (Granatstein, 1992). Over 80% of all dryland planted hectares in the PNW are planted to winter wheat, and almost 90% of harvested wheat in the region is exported (Kok *et al.*, 2009). Wheat grown in the region is primarily soft white, with a small portion of hard red winter and spring varieties (Schillinger *et al.*, 2006). Soft white wheats have starchy kernels that are suitable for biscuits, noodles, and pastries. Hard red varieties have higher gluten content and strength and are used for breads, cakes, and muffins.

The limiting factor for agricultural production in the PNW is rainfall (Schillinger *et al.*, 2008), and a linear relationship exists between available soil moisture and yield (Schillinger *et al.*, 2012). The region is divided generally into low (<300 mm), intermediate (300-450 mm) and high (>450 mm) rainfall areas. Most of the precipitation in the PNW comes in November to March, up to 60% of the typical 200 to 600 mm of its annual precipitation (Papendick *et al.*, 1983). Intermediate rainfall regions have a continual issue with unpredictable precipitation which limits and causes variable yields (Baumhardt and Anderson, 2006; Granatstein, 1992). Furthermore, because the PNW receives most of its moisture in the winter, plant growth is not active during times of high precipitation (Unger *et al.*, 2006). Timing of precipitation is a critical factor in total yield (Hollinger and Angel, 2010). Rains in May and June are more influential than those that come in April.

In the low and intermediate rainfall regions of the PNW, wheat-fallow rotations are common (Guy and Lauver, 2006), and occupy 1.7 million ha of the dryland farming region.

Annual cropping systems, including spring and winter crops, are more common in the high rainfall regions and are usually associated with less wind erosion and increased soil organic carbon (Schillinger *et al*., 2008). In intermediate-precipitation regions fallow is still common but winter wheat-spring wheat or winter wheat-spring barley-summer fallow crop rotations are possible. Spring pea (*Pisum sativum*) and chickpea crops can be utilized however hard red spring wheat is usually more profitable (Schroeder, *pers. comm.* 2018.). High rainfall regions rotations (approximately 0.7 million ha (Esser, 1998)) commonly have winter wheat grown every third year, and spring grown crops like wheat, barley (*Hordeum vulgare*), lentil (*Lens culinaris*), pea, and others are planted the other two years (Schillinger *et al.*, 2008). Spring legume crops perform well in these higher rainfall regions, but they have low crop residue and increase concern of water erosion (Guy and Lauver, 2006).

Conventional (primary and secondary) tillage is still the most common tillage practice in the PNW, providing good weed control before planting and optimal seed bed texture. Various tillage and residue management systems have been developed to manage water conservation (Hammel, 1996). Summer fallow allows for accumulation of soil nitrogen and stored water. However, the system is far from perfect with regards to water use. Evaporation in summer fallow decreases top soil moisture. The moisture stored deeper in the profile is difficult to be accessed due to low initial availability, explaining why water use in wheat-fallow systems is not fully efficient (Baumhardt and Anderson, 2006; Unger *et al*., 2006), utilizing only 40% of potential water (Peterson *et al*., 2001).

Conventional tillage also has negative impacts on soil erosion (Machado *et al.*, 2007). Due to the 30-45% graded slopes, water erosion is a major concern in the PNW (Bussacca, 1989). It has been estimated that on average 0-50 Mt ha^{-1} of soil is lost to erosion annually, while in extreme cases, as much as 450 Mt ha^{-1} of soil is lost (ESCS-FS-SCS, 1978; Hall *et al*., 1999), and as a result 40% of the region's top soil, as of 1995, has already been lost to erosion (Pimentel *et al*., 1995). Even with conservation efforts, as of 2005, 11 Mt ha^{-1} of soil is still lost annually (Kok *et al.*, 2009). Soil erosion from water is a major problem for 70% of the PNW Palouse where land is steeply sloped (CAST, 1975; Papendick *et al*., 1983). In addition, over applications of fertilizers can cause these nutrients to be lost to surface and ground water through runoff and leaching through the soil profile into ground water aquafers (Mahler *et al*., 2011). Wind soil erosion is most extreme during early spring and fall. Soils that are dry, particularly in the low precipitation regions, coarse textured, and unprotected soils are affected the most (Skidmore and Woodruff, 1968; Leggett *et al*., 1974).

Modern farming practices attempt to combat erosion and nutrient depletion issues which are becoming less sustainable. There are increasing trends whereby growers use less intensive tillage, more continuous cropping systems, and reduced fallow periods to combat erosion and general soil health. These changes have been catalyzed by advancements in chemical herbicide treatments that are effective and economical, planting equipment that can reliably plant seed into crop residues, and overall improvements in crop genetics (Schlegel *et al*., 2013).

3.2.2 Production problems in a predominant cereal (monoculture) systems

The winter wheat-fallow cropping system dominates dry and intermediate regions of the PNW because of economic incentives which include "commodity subsidies, farm programs, and global markets" (Roesch-McNally, 2018). Wheat-fallow productions systems have been successful here because of improvements to farm equipment, inorganic fertilizers, agrochemicals and their application, and of locally adapted cultivars (Altieri, 1998). Classified as planting wheat on previous wheat fields, monoculture wheat causes disease and pest issues, particularly grassy weed issues (Krupinsky *et al*., 2004).

In more recent year, grass weeds and herbicide resistant grass weeds have become the major problem in systems where wheat and barley predominant. The main grass weed problems facing PNW winter wheat production include: ryegrass; downey brome; and jointed goatgrass (Huggins *et al*., 2014). Removal of these weeds and volunteer cereals is paramount for sustainable cereal production, and grass plant residue hosts cereal diseases and insects (Hirnyck, 2003). Grass weeds decrease yields and are difficult to control because the weed cycle is not disrupted in fall planted winter wheat crops. Grass weed control in winter wheat production is often limited to cultivation and selective herbicides where herbicide resistance has not yet occurred. In contrast, broadleaf weeds can be controlled in cereal system with selective herbicide applications. (Machado *et al*., 2007).

Eliminating “green bridge” hosts, grass weeds and cereal volunteers, greatly reduces disease pressure on subsequent wheat crops (Esser, 1998). Fungal diseases pose a tremendous threat to PNW cereal production. Broadleaf rotation crops such as legume and *Brassica* allow better grassy weed control, can reduce cereal diseases, and diversifies soil biology (Pan and Schillinger, 2014; Kirby *et al*., 2017). Continuous cereal cropping increases disease severity especially where high straw residues exist because pathogens can persist near the soil in these conditions (Papendick and Moldenhauer, 1995). Finnigan (1994) reported drastic decreases in internodal damage and Take-all in wheat when it was planted after canola as compared to burning wheat stubble.

Monoculture cereal production, intensive tillage, and traditional fallow degrade soil health and long-term sustainability of PNW small grain production (Rasmussen *et al*., 1980; Rasmussen and Parton, 1994; Reicosky *et al*., 1995; Rasmussen *et al*., 1998; Machado *et al*., 2007). Soil organic carbon decreases and soil erosion increases in this production system (Machado *et al.*, 2007). Soil pH continues to decrease in fields under this production system, and has led to a layer of acid soil at fertilizer placement depth in northern Idaho. Yields decline dramatically below ideal pH conditions (Mahler and McDole, 1985). Globally, a 10-30% yield drop is expected when wheat is planted back to back. North American wheat production is unique in that its well fertilized soils accumulate similar organic carbon as wheat fields that are rotated with soybean, canola, pea, or lentil (Smagacz *et al*., 2016).

3.2.3 Cereal rotation options

Wheat growers in the PNW are experts, achieving high yields every year, but the traditional tilled practice causes erosion and sustainability problems (Schillinger *et al*., 2003; Kok *et al*., 2009). The wheat producing region is diverse in terms of environments and soil types, but crop diversity is extremely limited. Over the last 125 years, the PNW has relied on mono-cropping wheat with some integration of cool-season legumes (Schillinger and Papendick, 2008).

Spring barley and spring wheat are potential spring rotation crops with winter wheat. Planting these spring crops reduce both grassy and broadleaf weeds through spring cultivation. Including spring planted rotation crops reduced the rate of developing herbicide resistant weeds as fewer herbicide applications are necessary (Rainbolt *et al*., 2004). In reduced tillage systems, spring rotation crops are more important for weed control than in traditional tillage systems because of the lack of opportunity to mechanically kill weeds (Ball *et al*., 2008; Smith *et al.,* 1996).

In general wheat yields are higher following non-cereal crops compared to following cereals (Scarisbrick *et al*., 1986; Bourgeois and Entz, 1996; Kirkegaard *et al*., 1997; Guy and Karow *et al*., 1998). However, few broadleaf crops have shown agronomic and economic adaptation to the environmental conditions of the PNW dryland agriculture. Alternative crops such as pea, mustard, sunflower, corn and flax have been considered as rotation crops in the PNW, however, none of which were determined to be economically viable (Schillinger and Papendick, 2008) and inclusion of non-cereal crops is still very limited because of agronomic and economic challenges (Yorgey and Kruger, 2017). Over 100 years of small-grain cereal grain production has greatly increased farmers' experience and technology creating effective implementation of the region's best management practices (BMP).

Other common spring rotation crops include: barley (Carr *et al*., 2014), garbanzo bean (*Cicer arietinum*), pea, lentil (USADPLAC, 2015), and spring canola (*B. napus*) (Brown *et al*., 2008; Huggins *et al*., 2014; Pan *et al.*, 2017). In 1996, where spring crops are planted with winter wheat, barley accounts for 40% of hectarage, pea (production down replaced by chickpea) and lentil account for 40%, and the other 20% is a split of other alternative crops and grass seed (Schillinger *et al*., 2003). Today, spring barley acres are much lower, and most pea acres are being planted to garbanzo bean (Schroeder, *pers. comm.* 2018). These cropping options control weeds and decrease erosion but have not been identified as economically superior compared to growing only wheat. The lack of alternative rotation crops has caused PNW growers to encounter increased cereal disease, insect, and weed incidence, water and wind erosion, and reduced crop yields (Bewick *et al*., 2008; Schillinger and Papendick, 2008).

When comparing spring barley, spring wheat, pea, and spring canola as alternative crops it was determined that spring wheat was the most economically competitive. Spring barley was also found to be a well-adapted spring seed crop for this region (McClintick-Friddle, 2016). Spring barley is not recommended if other alternative crops are available because the diseases, weeds, and insects that thrive in it also are likely to affect winter wheat (Robertson and Stark, 2003). However, if spring crops are not expected to be harvest for seed, spring barley can be used as a cover crop to help maintain soil quality (Jacobs, 2016). Although, in practice this is more likely to be found in western Oregon and Washington (USDA-SARE, 2012).

Spring planted crops can be a risky investment in intermediate rainfall areas and virtually impossible to do economically in low rainfall areas (Williams *et al*., 2014). Although including spring crops can reduce soil erosion and weeds, planting spring crops is sensitive to variable precipitation, adding to the risk of including it in winter wheat rotations (Juergens *et al*., 2004).

Spring barley is commonly rotated with winter wheat and is highly adapted to the PNW intermediate and high rainfall regions. Barley has lower water use than wheat and can be grown in areas where less than 30 cm of rainfall occurs annually (Turner *et al*., 2001). Winter barley is not cold-hardy, and plants dies at temperature below -8º C, so crop failure is frequent with PNW winters (Jacobs, 2016). When winter barley survives winter conditions, seed yields are higher than spring barley. Over 95% of the barley grown in Washington State is spring barley (Turner *et al*., 2001).

3.2.3.1 Legume rotation options

Legume crops (pea, lentil and garbanzo bean) are not as competitive with weeds compared to other possible rotation options, (i.e. cereals or *Brassica* crops), but Legume crops offer growers many benefits in rotations (Syngenta, 2005). Spring pea will increase soil microbial life and provide niches for beneficial insects and microorganisms (Stepanovic *et al*., 2017). Garbanzo bean, as well as pea and lentil, do not use as much moisture as cereals or *Brassica* crops. Legume crops are shallow rooted, and mostly acquire water from the top 30 cm of soil (McVay *et al*., 2017). Legume crops reduce the need for applications of ammonium fertilizers which contribute to soil acidification (Koenig *et al*., 2011(b)).

Sub-regions of the PNW that receive more than 350 mm of annual precipitation have rotated spring pea and lentil with cereal crops for many years. Adequate rainfall and soil moisture are essential in legume production to ensure maximum seed yield and quality (Murray *et al*., 1987). Pea and lentil crops do not leave much crop residue compared to cereals or *Brassica* crops, so soil erosion is more severe (Hills, 2017). Spring pea and lentil produce between 450 and 900 kg ha^{-1} of above ground biomass which leaves more than 75% of the ground uncovered during winter months (Gareau and Guy, 1995; Gareau and Guy, 1997). There can be limited snow catch in areas that need to conserve moisture (Beck, 2011).

Winter pea and lentil, like their spring alternatives, fix nitrogen in the soil through the symbiotic relationship with nodulating bacteria, which can lower total greenhouse gas emissions. Many types of winter pea and lentil lack cold hardiness. Austrian winter pea (AWP) varieties, and the yellow pea ‘Windham’ (Schillinger, 2017), are cold-hardy and crop failure is rare in the PNW. AWP can be planted using the same equipment as winter wheat and has greater yields than spring pea (McGee *et al*., 2017). Winter legumes offer better erosion control than spring varieties because soil is not as exposed as fallow during winter months where the majority of PNW precipitation is received.

Winter wheat yields have been observed to increase 20% planted after pea as compared to planting after wheat (Guy, 2016). In Saskatchewan, Canada, it was determined that barley yields were 21% higher when following pea, lentil, and fava bean as compared to growing continuous barely (Wright, 1990). All legumes allow for different methods of controlling grassy weeds with different mode of action herbicides. Pea, garbanzo bean, and lentil are ideal rotation crops if growers want to reduce fertilizer costs based on their nitrogen fixation ability (USADPLC, 2015). Pea, garbanzo bean, and lentil are important crops to global agricultural production as they provide excellent protein and food security to areas struggling with increasing population issues (Chatuvedi *et al*., 2011). However, their limited crop residues are not conducive to reducing soil erosion (Ewing, 2015).

3.2.3.2 Brassica rotation options

Winter canola (mainly industrial rapeseed types) have been grown commercially in the PNW for over 100 years, and both spring and winter canola cultivars have been developed with high yield potential and good stress tolerance to PNW conditions (Davis *et al*., 2017a and 2017b).

Increased interest in biodiesel and canola food oil on the public and governmental level (Pan *et al.*, 2016) have “increased canola research, extension and production” (Pan *et al.*, 2017), and current value of canola compared to wheat is an important consideration. There is a high demand for canola oil in the PNW. Canola and rapeseed have many edible and industrial uses (Downey, 1966). Canola oil is used for frying, salad dressing, shortening, non-dairy fat substitutes, pet foods, and even supplemental vitamin E. Industrial uses include: lubricant, greases, plastics, bio-fuel feedstock, printing inks, lacquers, detergents, emulsifiers, fertilizers, pesticides, and use in asphalt (Downey, 1966).

Spring canola is a high biomass crop with a deep and extensive taproot system that protects soil from erosion better than either cereal and Legume crops (Myers, 2002). Canola crops can achieve competitive yields even when plant stands are low because they are good at utilizing available space in the field. Even when 50% of plants establish, maximum yields can nearly be achieved. The extensive root system is reported to penetrate deeper in a response to water limitation (Koenig *et al*., 2011a), can improve soil structure and access nutrients deep in the soil profile. These roots are unique for their ability to break up plow pans, increasing water infiltration, and mine nutrients deeper than cereals and legumes are capable. Nutrients are preserved instead of leaching into ground water and increases water infiltration through the soil (Guy and Gareau, 1997; Merril *et al.,* 2002, Weinert *et al*., 2002, Thorup-Kristensen *et al*., 2003, Vos and Van Der Putten, 2004, Malagoli *et al*., 2005, Dean and Weil, 2009).

It has been shown that growing herbicide tolerant spring canola helps combat weeds common to cereal fields (Painter *et al*., 2013). Including canola in cereal rotations is beneficial for weed control giving growers alternative herbicide chemistries (i.e. non-group 2 mode of action) for the control of grass weeds (i.e. Assure II or Roundup, Ignite).

Canola crops provide excellent disease and insect control in winter wheat rotations. Canola plants, like other Brassicaceae (i.e. rapeseed), contain glucosinolates, albeit at low concentrations, that can breakdown in the soil producing allelopathic toxic sulfur compounds that have been proven to have herbicidal (Hamilton, 2004; Handiseni, *et al.*, 2011), insecticidal (Lichtenstein *et al.*, 1964; Brown *et al*. 1991; Ross *et al.*, 2008), nematicidal (Mojtahedi *et al*. 1991; Mazzola, *el al.*, 2007; Mazzola, *el al.*, 2008) and fungicidal (Papavizas and Lewis 1971; Handiseni *et al.*, 2013) properties.

Including canola in crop rotations improves soil quality and wheat yields (Painter *et al*., 2013). Winter wheat yields following winter canola are higher than when following winter wheat because of better weed control, less soil erosion control, and greater crop diversity (McNabb, 2009). In the PNW winter wheat yield following winter canola have between 20 and 27% higher yield (Young *et al.*, 2014). A 2015 experiment investigating subsequent winter wheat yields following multiple the spring *Brassica* crops (*B. napus, B. juncea, B. carinata, B. rapa*, *Sinapis alba*, *or Camelina sativa)* determined there was no favorable species but they all improved wheat seed yield. However, there was a significant economic difference between the oilseeds, *B. napus* (spring canola) and *B. juncea* (condiment Indian mustard) being the most economically valuable (Ewing, 2015).

Integration of winter and spring canola into existing cereal rotations in the PNW is not without its issues. Although it has been claimed that water use efficiency in canola crops is comparable to wheat (Hocking *et al*., 1997), soil water availability and planting and fall establishment of winter canola is a limiting factor of crop production. Winter canola needs to be planted into soil moisture before the end of August hence summer fallow is required (Kephart and Murray, 1990). Adequate soil moisture is often not available in areas of the PNW that receive less than 350 mm of annual precipitation. It should be planted late enough that it does not deplete the soil moisture and early enough the plants are large enough to survive winter and compete against weeds. (Brown *et al*., 2008). In general, winter canola yields higher than spring canola, making it potential economically viable to alternate with winter wheat but its disadvantage is high water use (Huggins *et al*., 2014).

Additionally, a lack of insect resistant/tolerant cultivars necessitates the use of multiple insecticide applications in spring-planted canola (Brown *et al*., 1994). Delayed spring planting in Canada decreases seed yields (Degenhardt and Kondra, 1981; Hockings, 1993). Spring canola must be planted early in the spring to avoid high damaging summer temperatures at flowering, yet late enough to avoid spring killing frosts (Thomas, 1984). Also, spring canola yields can fluctuate due to semi-arid regions in the Palouse having unpredictable precipitation (Granatstein, 1992; Baumhardt and Anderson, 2006).

Despite all the advantages of canola crops, they are still not grown extensively in the PNW because they are economically risky (Esser and Hennings, 2012). Commercial production of winter and spring canola has not been fully integrated in the PNW due to agronomic and economic constraints (Pan *et al*., 2016) but research continues to demonstrate its potential throughout different PNW sub-regions (Brown and Davis, 2017).

3.2.4 Objectives of this experiment

The aim of study is to quantify the rotation effects of winter and spring canola by examining; (a) spring canola-winter wheat; spring pea-winter wheat; spring barley-winter wheat, and spring wheat-winter wheat rotations; and (b) winter canola-winter wheat; Austrian winter pes-winter wheat; summer fallow-winter wheat; and winter wheat-winter wheat two-year rotations of crop productivity and grower profitability. Specific objectives of study include:

- Determine the rotation effect of spring and winter crops on the yield of following winter wheat crops in a two-year rotation.
- Determine the effect of rotation crop on post-harvest water infiltration and water seepage; how it may impact the performance of following winter wheat crops.

3.3 Materials and methods

Two separate experiments were carried out, both to examine crop sequencing effects. One experiment examined spring crops followed by winter wheat, while the second examined winter crops (or fallow) followed by winter wheat.

3.3.1 Spring crop-winter wheat rotation trials

Spring rotation effects were examined in field trials grown at the University of Idaho Kambitsch Farm near Genesee Idaho. The Kambitsch Farm is located 15.3 km south of Moscow, Idaho (46˚55’N, 116˚92’W). Elevation is 815 m, with average annual rainfall between 1980 and 2010 of 50 cm. Soil type is Naff Palouse silt loam. It’s fine-silty, mixed, mesic typic Argixerolls.

The field trials were managed as a combination of conventional tillage and no-tillage. The previous crop before the spring crops was spring barley. Prior to planting the spring crops soil was managed with standard tillage, where ground was chisel plowed in fall. In spring, the trial area was harrow cultivated after application of a glyphosate spray for general weed control. Thereafter fertilizer applied and cultivated into the soil prior to final cultivation to incorporate it.

The spring sequence trial was planted in two cycles. Each cycle included 4 spring crops in Year-1 followed by a single winter wheat cultivar planted over all the whole trial area the following fall.

3.3.1.1 Cultivars

Four spring crop species were included in the Year-1 spring rotation: Spring wheat (‘Whit’, developed by Washington State University, Kidwell *et al.*, 2009); spring barley (‘Champion’, developed by WestBred LLC but now marketed by Highland Specialty Grains); spring canola (‘Star-402-RR’, Marketed by Star Specialty Seed Inc.); and spring green pea (‘Banner’, developed by the USDA Legume Breeding Program, Pullman, Washington).

3.3.1.2 Planting dates and seeding rates

Spring rotation crops were planted as early as it was possible to complete spring cultivation being on April 25th in 2016, and May 11th in 2017. All the cultivars chosen for the trial were highly adapted to growing conditions in northern Idaho and were indeed all grown commercially during the period the trials were evaluated.

The soft white winter wheat cultivar WB-1529 was planted over the complete Year-1 trial area in Year-2 on October 12th, 2016, while the soft white cultivar Brundage'96 was planted over the 2017 spring crops on September 30th, 2017. In each case, the wheat was direct seeded into the standing stubble of the harvested spring crops.

Prior to planting, 1,168 mL ha^{-1} Roundup RT3 in a 187 L ha^{-1} solution was applied as a broad-spectrum herbicide and mixed with 2,4-D (2,4-dichlorophenoxyacetic acid) to kill any spring canola volunteers.

Seeding rates used for the spring crops included: 90 kg seed ha^{-1} for spring barley; 6.7 kg seed ha^{-1} for spring canola; 146 kg ha^{-1} of seed for spring pea; and 112 kg seed ha^{-1} for spring wheat. Winter wheat in Year-2 was planted 112 kg seed ha^{-1}.

Seed was planted at an appropriate depth according to each crop: spring canola planted shallow at 1-2 cm; spring and winter wheat and spring barley planted to a depth of 2-4 cm and pea planted to 4-5 cm depth.

3.3.1.3 Plots dimensions and experimental design

The experimental design for each cycle of the trials was a Latin-square design where each spring crop was arranged in random with the restraint that each crop appeared once in each row and once in each column of the design. Each plot was 8.5 m x 11.7 m in dimension and each treatment was replicated 4 times. Year-1 plots were planted with a single-cone, double-disc plot planter. Year-2 winter wheat was planted over the whole year-1 trial area using a direct-seed commercial planter**.**

3.3.1.4 Fertilizer applied to spring rotation crops

Prior to planting each spring Year-1 crops, soil samples were taken from the trial area to determine base soil nutrients, and fertilizer applied to bring each crop up to the recommended N-P-K-S to recommended rates for the region. In 2016, 308 kg ha^{-1} of 31-10-0-7.5 was applied to trial areas where spring barley, canola, and wheat were to be planted, while areas where pea was to be planted had 112 kg ha^{-1} of 16-20-0-7.5 applied. In 2017, 351 kg ha^{-1} of 31-10-0-7.5 was applied to trial areas where spring barley, canola, and wheat were to be planted, while areas where pea was to be planted had 168 kg ha^{-1} of 16-20-0-7.5 applied. All fertilizer applied was mechanically incorporated prior to planting.

Fertilizer application applied to the Year-2 winter wheat varied according to which spring crop had been planted in Year-1 and soil samples taken from Year-1 plots after harvest. Two soil samples were taken from each plot using a 1.5 m soil probe pushed into the soil using a hydraulic press. The samples were separated into individual bags of 0.3 m sections. All sections were tested for NO_3, Moisture content. The top 0.3 m sections were additionally tested for P, S, NH_4, pH, organic matter concentrations.

In fall 2016, 112 kg ha^{-1} of 31-10-0-7.5 applied to the complete trial area. In addition, plots were top-dressed on May 2nd, 2017, with 46-0-0 at a rate of 152 kg ha^{-1} for the spring barley treatment, 137 kg ha^{-1} for the spring canola treatment, 142 kg ha^{-1} applied to the spring pea treatment, and 197 kg ha^{-1} applied to the spring wheat treatment.

In fall 2017, 224 kg ha^{-1} of 31-10-0-6.5 was applied to the complete trial area. In early spring of 2018, additional 31-10-0-6.5 fertilizer was top-dressed according to nutrient requirements based on soil sample data. 180 kg ha^{-1} was applied to the spring pea treatment, 362 kg ha^{-1} was applied to the spring barley treatment, 235 kg ha^{-1} was applied to the spring canola treatment, and 362 kg ha^{-1} was applied to the spring wheat treatment.

3.3.1.5 Pesticides applied to spring rotation crops

Pesticides were applied to different spring crops when needed to control weeds and diseases. In 2016, on June 1st, 877 mL ha^{-1} Huskie, 1,242 mL ha^{-1} Orion, 1,168 mL ha^{-1} Axial XL, 56 g ha^{-1} Affinity Broad Spectrum, and 0.25% v/v M-90 surfactant in a 187 L ha^{-1} solution was applied to spring barley and wheat to control weeds. Star-402-RR is a Roundup Ready® spring canola cultivar, and 1,168 mL ha^{-1} Roundup RT3 in a 187 L ha^{-1} solution was applied to control weeds in the canola plots when the crop reached the 4-6 leaf stage. To control weeds, on June 1st, in pea 2,336 mL ha^{-1} Basagran plus 1,750 mL ha^{-1} crop oil was applied in a 187 L ha^{-1} solution. To control pea and canola insect-pests, 139 mL ha^{-1} Warrior II insecticide was applied. To control blackleg disease in the canola plots, 292 mL ha^{-1} Priaxor Xenium fungicide was tank mixed with the Warrior II, and 1.25% v/v R56 in a 159 L ha^{-1}, applied on June 4th. To control late-season insects, aphids, the complete spring trial area was aerially sprayed with 139 mL ha^{-1} Warrior II on July 14th.

In 2017, 139 mL ha^{-1} Warrior II and 1.25% v/v R56 in a 168 L ha^{-1} solution was applied to spring canola and pea on May 28th to control early season insects. On June 2nd, 877 mL ha^{-1} Huskie, 1,242 mL ha^{-1} Orion, 56 g ha^{-1} Affinity Broad Spectrum, and 0.25% v/v M-90 surfactant in a 196 L ha^{-1} solution was applied to all barley and wheat plots to control weeds. On June 6th, 1,168 mL ha^{-1} Roundup RT3 in a 280 L ha^{-1} solution was applied to spring canola plots to control weeds. Weeds in pea plots were controlled by application of 2,300 mL ha^{-1} Basagran, 2,800 mL ha^{-1} ammonium sulfate, and 1,750 mL ha^{-1} crop oil in a 280 L ha^{-1} solution.

In both years, 877 mL ha^{-1} Huskie, 1,242 mL ha^{-1} Orion, 56 g ha^{-1}Affinity Broad Spectrum, and 0.25% v/v M-90 surfactant in a 196 L ha^{-1} solution was applied to all the Year-2 winter wheat plots in early June for weed control.

3.3.1.6 Variates recorded of all rotation experiment crops

Each spring crop was visually assessed for crop emergence (on a 1-9 scale, where 1= very poor crop establishment, 9= very good crop establishment) four weeks after planting. Days from January 1st to flowering (heading for wheat) was recorded when 50% of flowering or heading was observed. Plant height after flowering or heading was recorded in cm. Seed yield was recorded after seed was dried for two or more days at 43 °C. Test weight procedures were carried out on cereal crops after yield was recorded following the procedure outlined by Hammond (1991) using a Newport MKIIIA Nuclear Magnetic Resonance (NMR) Analyzer (Oxford Instruments Inc.; Concord, MA).

3.3.1.7 Harvest time of spring rotation crops

At maturity, the spring plots were harvested using a small-plot combine (Wintersteiger Nurserymaster Elite™ (Wintersteiger, Inc.; Salt Lake City, UT)). A single 1.96 m x 11.6 m center strip was harvested from each plot and bagged. Canola and pea seed were air dried at 43°C for 48 hours prior to being weighed. Spring barley and wheat were weighed direct from the combine. Spring rotation crops were harvested on August 26th in 2016 and August

15th on 2017. Test weight was determined on seed from each spring barley and wheat plot, although data are not presented in this thesis.

Year-2 winter wheat was harvested in a similar manner according to plots associated with the area where the four spring crops were grown. Year-2 winter wheat was harvested on August 15th in 2017, and September 3rd in 2018. Again, a single 1.96 m x 11.6 m center strip was harvested from each plot and bagged prior to weighing and test weight determination.

3.3.2 Winter crop-winter wheat rotation trials

Four different winter crop rotations were examined including: (1) winter wheat-winter wheat; (2) winter canola-winter wheat; (3) Austrian winter pea (AWP)-winter wheat; and (4) fallow-winter wheat. These two-year rotations were chosen as representative, or at the least possible, in the intermediate to high rainfall regions of the PNW. The winter sequence trial was planted in two cycles. Each cycle included 3 winter crops, plus a fallow treatment, in Year-1 followed by a single winter wheat cultivar planted over all the whole trial area the following fall (Year-2).

3.3.2.1 Location, climate, soil of winter rotation trial

The winter crop-winter wheat rotation trials were grown at the University of Idaho Parker Farm located 3.2 km east of Moscow, Idaho (46˚73’N, 117˚W). The farm is at an elevation of 785 m, with average annual precipitation between 1981 and 2010 of 69 cm. Soil type is Palouse silt loam, deep and well drained, formed in loess on hills. It is fine-silty, mixed, superactive, and mesic Pachic Ultic Haploxerolls.

The field trials were managed as a combination of conventional tillage and no-tillage. The previous crop before the Year-1 winter rotation crops was winter wheat. Prior to planting the Year-1 winter crops soil was managed with standard tillage, where ground was disc-plowed first to a depth of 20 cm, then heavily harrowed. After harrowing, the complete trial area was irrigated with 5-6 cm of irrigation water, then after application of a glyphosate spray for general weed control, lightly harrowed before planting the Year-1 fall crops. Thereafter fertilizer hand applied to each plot and cultivated into the soil.

3.3.2.2 Cultivars

The cultivars chosen for this study were all highly adapted to the region in which the trials were grown. 'Amanda' (Brown, *et al.,* 2012) winter canola was developed at the University of Idaho and has been planted on a high proportion of acreage in the PNW. 'UI-WSU Huffman' (Brown *et al.*, 2018) is a soft while winter wheat cultivar with excellent end-use quality and highly resistant to strip-rust and *Celphsporium* strip. 'Granger' Austrian winter pea (Muehlbauer *et al.*, 1998) is a feed-quality winter pea developed in collaboration with the USDA, Washington State University and the University of Idaho, with good cold tolerance and adaptability to the PNW. Fallow treatment remained un-planted in Year-1 of the rotation study. Weeds in the fallow treatment were controlled by herbicide application throughout the Year-1 growing season. The complete trial area in Year-2 was planted to soft white winter wheat cultivar 'WB-1529'.

3.3.2.3 Planting dates and seeding rates

Year-1 winter crops were planted slightly later than might be recommended for winter canola, yet slightly earlier than would be traditional for winter wheat and AWP. This was done to allow for planting all the Year-1 plots at the same time. Before planting, 3.8 cm of irrigated water was applied to the field. Year-1 plots were planted on September 3rd in 2015, and September 14th in 2016. UI-WSU Huffman winter wheat was direct-seed planted into the Year-1 crops stubble from the Year-1 trial area on October 4th in fall of 2016 (over the 2015-2016 Year-1 trial), and on October 15th in 2017 (after the 2016-2017 Year-1 trial). Prior to planting, 1,168 mL ha^{-1} Roundup RT3 in a 187 L ha^{-1} solution was applied as a broad-spectrum herbicide to control weeds and volunteers from the Year-1 crops. Seeding rates used for winter wheat was 140 kg seed ha^{-1}, for winter canola 7.9 kg seed ha^{-1} of seed, and for AWP 112 kg seed ha^{-1}.

3.3.2.4 Plots dimensions and experimental design

The experimental design for each cycle of the trials was a Latin-square design where each spring crop was arranged in random with the restraint that each crop appeared once in each row and once in each column of the design. Each plot was 8.5 m x 11.7 m in dimension and each treatment was replicated 4 times. Plots were planted with a single-cone double-disc plot planter.

3.3.2.5 Fertilizer applied to winter rotation crops

Soil samples were taken from Year -1 crops in spring to determine base soil nutrients, and fertilizer applied to bring each crop up to the recommended N-P-K-S to recommended rates for the region. In spring 2016, April 14th, 254 kg ha^{-1} of 31-10-0-7.5 was applied to the Year-1 winter canola plots, 262 kg ha^{-1} of 31-10-0-7.5 was applied to the Year-1 winter wheat plots. In spring of 2017, 189 kg ha^{-1} of 31-10-0-7.5 was applied to the Year-1 winter canola and winter wheat plots. Fertilizer was applied via topdressing. No fertilizer was applied to the Year-1 fallow plot areas. In fall 2017, 224 kg ha^{-1} 16-20-0-13 was applied to the whole Year-1 trial area.

Fertilizer application applied prior to planting the Year-2 winter wheat varied according to which winter crop had been planted in Year-1, and soil samples taken from Year-1 plots after harvest. Two soil samples were taken from each plot using a 1.5 m soil probe pushed into the soil using a hydraulic press. The samples were separated into individual bags of 0.3 m sections. All sections were tested for NO_3, and moisture content. The top 0.3 m sections were additionally tested for P, S, NH_4, pH, organic matter concentrations.

In fall 2016, 112 kg ha^{-1} of 31-10-0-7.5 applied to the complete trial area. In addition, plots were top-dressed on April 17th, 2017, with 46-0-0 at a rate of 172 kg ha^{-1} after winter wheat, 66 kg ha^{-1} after spring canola, 84 kg ha^{-1} applied after AWP, and 54 kg ha^{-1} applied after fallow treatment.

In fall 2017, 224 kg ha^{-1} of 31-10-0-6.5 was applied to the complete trial area. In spring 2018, 31-10-0-6.5 was top-dressed on plots depending on soil sample data. 145 kg ha^{-1} was applied to the AWP treatment, 145 kg ha^{-1} was applied to the fallow treatment, 325 kg ha^{-1} was applied to the winter canola treatment, and 452 kg ha^{-1} was applied to the winter wheat treatment.

3.3.2.6 Pesticides applied to winter rotation crops

Pesticides were applied to different Year-1 winter crops when needed to control weeds and diseases.

In 2015, on September 9th, before plants had emerged, and again on September 21st, to the pea and canola, 207 mL ha^{-1} Assure II (quizalofop) and 0.25% v/v M-90 surfactant in a 149.5 L ha^{-1} solution was applied to control severe volunteer winter wheat. On October 1st, canola, pea, and fallow received 237 mL ha^{-1} Select 2EC, 1,100 g ha^{-1} ammonium sulfate, and 1.0% v/v crop oil in a 205.5 L ha^{-1} solution. Assure II (quizalofop) limits were reached on pea (415 mL) and canola (532 mL).

In 2016, on April 13th, canola received 292 kg ha^{-1} Stinger herbicide and 0.25% v/v M-90 surfactant in a 205.5 L ha^{-1} solution to control mayweed chamomile. Wheat received 292 mL ha^{-1} Priaxor fungicide for stripe rust control, 877 mL ha^{-1} Huskie, 1,168 mL ha^{-1} Axial-XL, 57 g ha^{-1} Affinity Broad Spectrum, and 0.25% v/v M-90 surfactant in a 205.5 L ha^{-1} solution. Pea were hand weeded, receiving no herbicides.

3.3.2.7 Harvest time of winter rotation crops

At maturity, the Year-1 winter plots were harvested using a small-plot combine (Wintersteiger Nurserymaster Elite[tm] (Wintersteiger, Inc.; Salt Lake City, UT)). Prior to combine harvesting canola plots were swathed on July 2nd in 2017 and harvested on July 15th in 2017. In 2016, winter canola plots were direct harvested without swathing, on July 21st. Winter wheat and AWP were harvested on July 28th, in 2016. Winter wheat and AWP harvested on August 3rd in 2017.

A single 1.96 m x 11.6 m center strip was harvested from each winter canola and winter wheat plot, and two 1.96 m x 11.6 m strips harvested from each AWP plot, and seed from each bagged. Winter canola and AWP seed were air dried at 43°C for 48 hours prior to being weighed. Seed from winter wheat plots were weighed direct from the combine. Test weight was determined on seed from each winter wheat.

Year-2 winter wheat was harvested in a similar manner according to plots associated with the area where the three Year-1 winter crops and fallow were grown. Year-2 winter wheat was harvested on August 16th in 2017, and September 8rd in 2018. Again, a single 1.96 m x 11.6 m center strip was harvested from each plot and bagged prior to weighing and test weight determination.

3.3.3 Variates recorded of all rotation experiment crops

Each spring and winter crop were visually assessed for crop emergence (on a 1-9 scale, where 1= very poor crop establishment, 9= very good crop establishment) four weeks after planting. Days from planting (spring crops) or January 1st (winter crops) to flowering or heading was recorded when 50% of flowering or heads was observed. Plant height after flowering or heading was recorded in cm. Seed yield was recorded after seed was dried for two or more days at 43 ºC. Test weight procedures were carried out on cereal crops after yield was recorded.

3.3.4 Soil infiltration

Water infiltration into soils after crop harvest was determined on all spring and winter crops from the Year-1 trials. Water infiltration was determined using a 25 cm diameter metal cylinders, 20 cm tall, which was imbedded 2 cm into the soil surface, and then 1 liter of water was poured into the cylinder, and the time in minutes and seconds recorded according to the time it took for the 1 liter of water to infiltrate into the soil.

In addition, it was noted that a proportion of the water would ‘seep’ from the side of the cylinder rather than percolate into the soil. To assess this, we recorded water seepage as the proportion of the circumference of the cylinder where seepage was noted, plus the distance that the seepage was observed from the side of the cylinder (Figure 3.1). These two values were used to estimate area of seepage outside of the cylinder using this equation: $[\pi(r_1 + r_2)^2 - \pi r_1^2]$ x (*Prop*) = Seepage area. Where r_1 is distance from center of the cylinder to edge of seepage, r_2 is the radius of the cylinder (i.e. 25 cm), and *Prop* is proportion of the cylinder circumference where seepage was observed. Seepage was determined on the spring rotation plots on September 27th in 2016 and August 10th in 2017, and on winter rotation plots on August 19th in 2016 and August 9th in 2017.

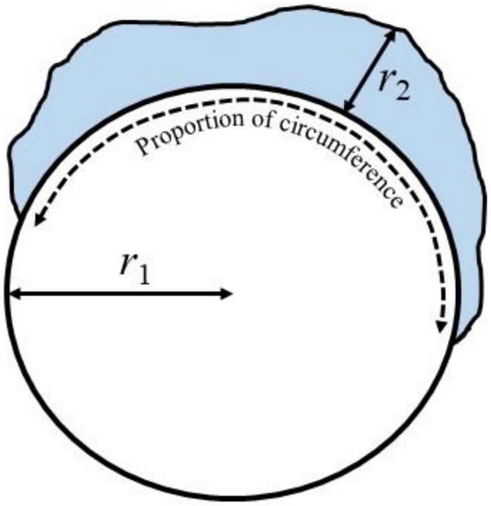

Figure 3.1 Diagrammatic representation of how seepage was calculated.

3.3.5 Data analysis

Data was analyzed using a general linear model, Duncan’s multiple range tests (SAS, 2010). In the analyses of variance, significance differences between years was tested using the replicates *within* year mean square (Error 1). The effect of crop and the interaction crop x year was tested using the general, pooled error (Error 2).

Economic analyses were based on gross return to growers and was based on Chicago Board of Trade and local elevator commodity seed prices of \$0.192 kg^{-1} (5.24 bu^{-1}) for soft white wheat, \$0.154 kg^{-1} (\$140 ton^{-1}) for barley, \$0.484 kg^{-1} (\$22 cwt^{-1}) for canola, and \$0.276 kg^{-1} (\$251 ton^{-1}) for pea and AWP.

3.4 Results and Discussion

3.4.1 Spring-winter Rotations

Mean squares from the analyses of variance of Year-1 spring rotation crop yield and gross return, yield and gross return of winter wheat following each of the spring rotation crops, and two-year gross return from each of the four spring-winter rotations (Table 3.1). Significant differences between years were observed for rotation crop yield and gross return, and two-year gross return. There were no differences between the two years of winter wheat following the spring rotation trials yield or gross return.

Highest spring crop yield was obtained from spring barley (5,064 kg ha^{-1}), and spring wheat (4,593 kg ha^{-1}), intermediate seed yield from spring canola (2,257 kg ha^{-1}), and lowest spring crop yield was from pea (1,484 kg ha^{-1}) (Table 3.2). Despite a significant crop x year interaction for seed yield, the crops performed relatively consistently over the two years. Spring canola performed proportionally lower in 2017 which may explain the significance of the interaction.

Averaged over two years, greatest gross return was from spring canola (\$1,092 ha^{-1}), followed by spring wheat (\$882 ha^{-1}), barley (\$780 ha^{-1}), and pea (\$410 ha^{-1}) (Table 3.3). It should, however, be noted that gross return is a combination of seed yield and commodity seed price, and at the time of analyses the price of cereals (wheat and barley) was relatively lower and the price of canola (\$0.48 kg^{-1}) was higher than it had been in several years. There was a significant interaction between crop gross return and years, and there was only significant difference in gross return in the 2016 year with no difference in gross return in 2017.

Yield of winter wheat following the four spring crops was lower than what is traditionally expected in that area (Table 3.4). Again, there was a significant interaction between crop yield and years. In 2016, winter wheat seed yield following spring wheat was significantly higher than either of the three other spring-winter rotations. In 2017, highest winter wheat seed yield was following spring canola, which was significantly higher than spring barley-winter wheat or pea-winter wheat rotations. However, average winter wheat yield following spring wheat showed greatest yield was significantly higher than other spring rotations. Consequently, cash return of winter wheat following the four spring crops followed the same pattern as the winter wheat yield, given that all seed harvested have same value (Table 3.5), and no further details are necessary.

Water infiltration and water seepage effects were not significantly different after harvest of the four spring crops (Table 3.6 and Table 3.7), albeit that these were markedly different infiltration rates and seepage observed. Identifying differences in water infiltration is important for predicting water storage potential of rotation crops and water seepage is important for predicting water runoff. Water infiltration rates after spring canola and barley were much higher (40 and 42 l h^{-1}, respectively), compared to spring wheat and pea (16 and 17 l h^{-1}, respectively). The tap root structure of canola is supposed to break up soil more than cereals and peas, yet, our results do not indicate a major difference between spring canola and spring pea. Compared to soil in fall planted fields which experiences extreme precipitation during winter months followed by a drying period, soil in spring planted fields that has been tilled, meaning it has less time to form different shaped soil aggregates based on spring crop variety. Furthermore, the shorter grow season limits time for root structure differentiation between crops meaning they will be smaller and less capable of impacting soil as much as fall planted crops. Similarly, greatest seepage was observed from the two cereal crops compared to the broadleaf crops. Most research pertaining to erosion has to do with variable stubble by crop variety. A possible explanation for the variation in water seepage observed lies in that pulse crops use less water and canola is able to access water from deeper in the soil compared to cereals. Soil on the surface where cereals were planted could have created greater horizontal capillary action because it was drier. Overall, spring canola appears to be beneficial to soil health characteristics (McClintick-Friddle, 2016).

3.4.2 Winter-winter rotations

Results from the winter-winter rotations were markedly different to those from the spring-winter rotation studies, and there were generally greater crop differences with the winter-winter rotations. Crop differences were the only significant interactions for Year-1, gross return, and gross return over two years (Table 3.8).

Winter wheat seed yield (6,881 kg ha^{-1}) in the Year-1 winter crop trials produced significantly higher yield than winter canola (3,841 kg ha^{-1}), which in turn was significantly higher than from AWP (867 kg ha^{-1}) (Table 3.9). Obviously, there was no yield harvested from the fallow treatment, and again the relative yield of crops was consistent over years. High canola commodity prices over those for wheat resulted in greater gross return to farmers from winter canola. Winter canola was \$1,859 ha^{-1} greater return compared to winter wheat (\$1,322 ha^{-1}), and gross return for AWP (\$239 ha^{-1}) would hardly cover the costs to grow the crop, and fallow returns no value to growers in that fallow year (Table 3.10).

There were significant differences in the yield of winter wheat following the 3 winter crops and fallow treatment (Table 3.11). Winter wheat following AWP and winter canola (7,029, and 6,731 kg ha^{-1}, respectively) where significantly higher than winter wheat following winter wheat. Surprisingly, the yield of winter wheat planted into fallow ground also was significantly lower than wheat after AWP or canola (Lyon *et al*., 2004; McClintick-Friddle, 2016). It is possible that the low rate of water infiltration and high rate of water seepage played a role in decreasing available moisture for subsequent wheat crops following fallow. And, although weeds were chemically controlled, volunteer wheat and grassy weeds occurred at high rates in fallow plots. Observations of the winter rotation trial showed that there was visibly higher grass weed infestation in the wheat-wheat rotation plots compared to the other rotations. As with the spring rotation trials, gross return of winter wheat following the four spring crops followed the same pattern as the winter wheat yield, given that all seed harvested have same value (Table 3.12), and no further details are necessary

One factor which could have contributed to the advantageous effect of winter canola on winter wheat yield was water infiltration. Crops had a significant impact on water infiltration and crops x year had a significant impact of water seepage (Table 3.13). Water infiltration following winter canola harvest (27 l h^{-1}) was significantly higher than after winter wheat, AWP or fallow treatment. Although, winter wheat yielded well following AWP, indicating water infiltration is not entirely responsible for benefiting subsequent wheat crops (Wright, 1990; Guy, 2016). Greatest seepage was observed on the fallow treatment plots (Table 3.14). It should be noted that we used chemical fallow in this study (rather than the traditional fallow of the dryland PNW which has a mulch of powdery soil on the soil surface to reduce water loss) and that the surface of the fallow ground was hard after baking over summer. This must have impacted water infiltration and seepage on the fallow treatment. Winter wheat following winter canola produced 1,138 kg ha^{-1} (17 bu acre^{-1}) higher seed yield than winter wheat following winter wheat (Table 3.16). Winter wheat planted into fallow ground showed little advantage over winter wheat following winter wheat. Both suggest that water infiltration would have an effect.

For spring and winter two-year gross returns, canola was significantly highest (Table 3.15, Table 3.16). Although spring and winter rotations were not compared directly it appears winter canola-winter wheat ($3,152 ha^{-1}) is more economically valuable than spring canola-winter wheat ($1,949 ha^{-1}). Fallow periods were not included as part of the winter canola rotation. The gross return for two years should be considered part of a three-year rotation and winter canola yields would likely have been higher if planted after a fallow period.

3.5 Conclusions

Eight different two-year rotations were examined (four spring crop-winter wheat and four winter crop-winter wheat). In general, there were greater rotational effects on the winter-winter rotations compared to the spring-winter rotations. This might have been expected as the latter allowed greater influence from spring cultivation which could have reduced weed infestations. Indeed, it is common practice in the PNW that farmers include spring crops into rotations with winter wheat mainly for grass weed control.

Gross return to farmers is not always the most appropriate measure of success in a crop rotation system because obviously crop prices change, often on a daily if not seasonal basis. However, it is common to use gross return to compare different crop sequencing option.

It was somewhat surprising that highest winter wheat following spring crops was from the spring wheat-winter wheat rotation. The reason for this was not obvious from observations we made. Perhaps, beneficial mycorrhizal fungi survived between spring wheat harvest and winter wheat planting which would not likely have existed in plots where winter wheat was planted after spring canola or spring pea. Alternatively, the broadleaf crops may have been host to detrimental fungi which reduced performance of following wheat crops. And, winter wheat following spring wheat is very common in the farming community. Either way, it has long been recognized that wheat is highly productive in the PNW, out-yielding wheat from all other US states (USDA, 2018). In this study, however, the winter wheat yields were less than expected PNW yields.

Advantageous canola prices showed a significant two-year gross return (\$1,949 ha^{-1}) from spring canola-winter wheat over spring wheat-winter wheat (Table 3.15) and including spring canola into the rotation increased two-year gross returns by \$149 ha^{-1}, albeit that including spring canola did not increase winter wheat yield compared to spring wheat, contrary to assumption (Scarisbrick *et al*., 1986; Bourgeois and Entz, 1996; Kirkegaard *et al*., 1997; Guy and Karow *et al*., 1998), and a reversal in pricing would give a different result. Also, in 2017, the spring canola yields were surprising low. Pea-winter wheat rotations were not favorable due to low pea yield and pea prices, and it would be unlikely that farmers growing only a pea-winter wheat rotation would cover the cost of growing the crops. This conclusion is speculative because we assume the lack fertilizer costs is not greater than the difference we encountered.

Two-year gross returns from winter-winter rotations were markedly higher than those from the spring-winter rotations examined (Table 3.16). An explanation for this is the poor total performance of winter wheat at Kambitsch Farm (spring rotation location). The highest two-year gross return was from a winter canola-winter wheat rotation (\$3,152 ha^{-1}), and lowest from AWP-winter wheat (\$1,589 ha^{-1}) or fallow-winter wheat (\$1,121 ha^{-1}). It should be noted, however, that winter canola is traditionally planted into summer fallow and hence the two-year return should more appropriately cover three growing seasons. Over three years the fallow-winter canola-winter wheat rotation returned \$1,051 ha^{-1} a year (\$3,152 over 3 years), which is not much less than \$1,198 ha^{-1} a year (\$2,397 over 2 years) possible with winter wheat-winter wheat rotations without fallow, especially as a fallow year would incur less costs than growing a wheat crop and offers other benefits. AWP, returning \$795 (\$1,589 ha^{-1} over 2 years), would not make including AWP more attractive to growers than winter canola or winter wheat.

Winter wheat following winter canola had higher seed yields than following winter wheat. Winter canola had the best water infiltration and AWP and winter canola were best for water seepage. Water infiltration and water seepage were significantly different between winter canola, wheat and AWP crops and could have advantageous effects on following wheat crops. It has long been recognized that the deep-rooted taproot of winter canola can have advantageous effects of soil properties and water infiltration compared to fibrous rooted cereal crops, yet few, if any studies have examined these effects (Chan and Heenan, 1991). Here, poor water infiltration into fallow ground, plus excellent infiltration into winter canola ground could explain a portion of the differences in yields observed. Additional effects such as weed and disease pressure contribute to the lack of success of winter wheat following winter wheat. Weed pressure was particularly strong, whereas, disease pressure was highly controlled.

Grass weed infestation in winter wheat-winter wheat rotation plots most certainly impacted the yield of wheat following winter wheat. Unfortunately, there appears to be fewer and fewer options to growers to control grass weeds in cereal crops and herbicide resistance is wide-spread. Including a broadleaf crop (like canola or AWP) into a rotation would allow alternative weed management strategies and offer different herbicide chemistries to growers. Group II (ALS-inhibitors) herbicides are common methods of control of grassy weeds in cereal crops in the PNW. However, they should not be used more than once every three years so chemically resistant grass weeds do not develop. Including a broadleaf crop that is as economically successful as winter wheat in winter wheat rotations would decrease the need for using Group II more than once every three years. In addition, availability of Roundup Ready™ canola in cereal rotations offers broad spectrum grass weed control chemistry not possible with other rotation crops.

Overall, spring rotation crops had a lesser impact on the productively and hence profitability of spring crop-winter wheat rotations but including winter canola into rotations with winter wheat have significant and monetary benefits to growers.

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Table 3.1. Mean squares and significance levels from the analyses of variance of Year-1 spring rotation crop yield and gross return to growers and following Year-2 winter wheat yield and gross return, and 2-year grows return to growers from spring wheat-winter wheat, spring barley-winter wheat, spring canola-winter wheat, and pea-winter wheat rotations grown over two years (cycles).

		Mean Squares									
Source of Variation	d.f.[a]	Crop Yield		Gross Return		Winter Wheat Yield		Winter Wheat Gross Return		Gross Return Two-years	
Year	1	23,971,009	***	1,849,382	***	594,145	ns	21,932	ns	2,274,108	***
Error (1)†	6	326,378	ns	16,214	ns	751,991	ns	27,759	ns	117,377	ns
Crops	3	24,428,430	***	652,877	***	606,784	ns	22,399	ns	2,352,821	***
Crops x Year	3	1,025,646	***	273,652	***	928,661	ns	34,281	ns	528,805	***
Error (2)	29	122,704		6,133		383,623				18,137	
Model error (R^2)		98%		99%		58%					

ns = not significant; *** = P<0.001; † Error(1) = Rep *within* Years; [a] Degrees of freedom

Table 3.2. Seed yield of spring wheat, spring barley, spring canola, and pea grown in Year-1 of the spring rotation trials.

Crop/Cultivar	2016		2017		Average	
	--------------------		kg ha^{-1}		---------------------	
Spring wheat	5,676	a	3,507	b	4,593	b
Spring barley	6,058	a	4,069	a	5,064	a
Spring canola	3,307	b	1,206	c	2,257	c
Spring pea	1,815	c	1,152	d	1,484	d
Average	4,214		2,484		3,350	

Means assigned to different superscript letters are significantly different (P<0.05).

Table 3.3. Gross return† to grower of spring wheat, spring barley, spring canola, and pea grown in Year-1 of the spring rotation trials.

Crop/Cultivar	2016	2017	Average
	-------------------- $ ha^{-1}	---------------------	
Spring wheat	$1,091 ^{b}	$674	$882 ^{b}
Spring barley	$933 ^{c}	$627	$780 ^{c}
Spring canola	$1,601 ^{a}	$584	$1,092 ^{a}
Spring pea	$501 ^{d}	$318	$410 ^{d}
Average	$1,032	$551	$791

† Based on commodity seed prices of $0.192 kg^{-1} for soft white wheat, $0.154 kg^{-1} for barley, $0.484 kg^{-1} for canola, and $0.276 kg^{-1} for pea and AWP.

Means within columns assigned to different superscript letters are significantly different ($P<0.05$).

Table 3.4. Seed yield of winter wheat grown in Year-2 after spring wheat, spring barley, spring canola, and pea grown in Year-1 in the spring rotation trials. Data presented are averaged over two years of experimentation.

Crop/Cultivar	2016	2017	Average
	-------------------- kg ha^{-1}	---------------------	
Spring wheat	5,295 ^{a}	4,257 ^{ab}	4,776 ^{a}
Spring barley	4,391 ^{b}	3,899 ^{b}	4,154 ^{b}
Spring canola	4,163 ^{b}	4,754 ^{a}	4,458 ^{ab}
Spring pea	4,341 ^{b}	4,188 ^{b}	4,265 ^{ab}
Average	4,548	4,275	4,413

Means within columns assigned to different superscript letters are significantly different ($P<0.05$).

Table 3.5. Gross return to grower of winter wheat grown in Year-2 after spring wheat, spring barley, spring canola, and pea grown in Year-1 in the spring rotation trials.

	2016		2017		Average	
	--------------------		$ ha^{-1}		--------------------	
Spring wheat	$1,017	a	$818	b	$918	a
Spring barley	$843	b	$749	b	$796	b
Spring canola	$799	b	$913	a	$857	ab
Spring pea	$834	b	$804	b	$819	ab
Average	$873		$821		$848	

Based on commodity seed prices of $0.192 kg^{-1} for soft white wheat, $0.154 kg^{-1} for barley, $0.484 kg^{-1} for canola, and $0.276 kg^{-1} for pea and AWP.
Means assigned to different superscript letters are significantly different ($P<0.05$).

Table 3.6. Means squares and significance levels from the analyses of variance of water infiltration and water seepage after harvest of spring wheat, spring barley, spring canola, and pea grown in Year-1 of the spring rotation trials.

		Mean Squares			
Source of Variation	d.f.[a]	Water infiltration		Water Seepage	
Year	1	20,299.1	**	757.7	ns
Error (1)†	6	1,292.6	ns	298.2	ns
Crops	3	1,686.6	ns	477.7	ns
Crops x Year	3	1,601.8	ns	198.9	ns
Error (2)	29	1,635.1		333.3	
Model error (R^2)		56%		43%	

ns = not significant; ** = $0.01>P>0.001$; † Error(1) = Rep *within* Years;
[a] Degrees of freedom

Table 3.7. Water infiltration and water seepage after harvest of spring wheat, spring barley, spring canola, and pea grown in Year-1 of the spring rotation trials. Data presented are averaged over two years of experimentation.

Crop/Cultivar	Water Infiltration	Water Seepage
	- liters hour^{-1} -	-- cm^{-2} --
Spring wheat	15.62	23.50
Spring barley	40.19	14.84
Spring canola	42.90	9.79
Spring pea	17.38	5.52
Average	29.02	13.41
LSD 5%	42.48	19.18

Table 3.8. Mean squares and significance levels from the analyses of variance of Year-1 winter rotation crop yield and gross return to growers and following Year-2 winter wheat yield and gross return, and 2-year grows return to growers from winter wheat-winter wheat, winter canola-winter wheat, AWP-winter wheat, and fallow-winter wheat rotations grown over two years (cycles).

		Mean Squares									
Source of Variation	d.f.[a]	Crop Yield		Gross Return		Winter Wheat Yield		Winter Wheat Gross Return		Gross Return Two-years	
Year	1	109,227	ns	780	ns	5,686,671	ns	209,960	ns	234,491	ns
Error(1)†	6	416,436	ns	24,633	ns	9,332,983	ns	57,366	ns	73,761	ns
Crops	3	73,332,995	***	5,768,553	***	10,839,592	ns	133,357	ns	5,213,186	***
Crops x Year	3	1,492,574	ns	76,142	ns	665,636	ns	8,191	ns	106,921	ns
Error(2)	29	561,232		36,422		1,631,083		60,201		154,859	
Model error (R^2)		93%		97%		52%		52%		91%	

ns = not significant; *** = P<0.001; † Error(1) = Rep *within* Years; [a] Degrees of freedom

Table 3.9. Seed yield of winter wheat, winter canola, AWP, and fallow grown in Year-1 of the winter rotation trials.

Crop/Cultivar	2016	2017	Average
	-------------------- kg ha^{-1}	--------------------	
Winter wheat	6,164 ^{a}	7,598 ^{a}	6,881 ^{a}
Winter canola	3,937 ^{b}	3,744 ^{b}	3,841 ^{b}
AWP	1,254 ^{c}	479 ^{c}	867 ^{c}
Fallow	0 ^{d}	0 ^{c}	0 ^{c}
Average	3,785	3,940	3,863

Means assigned to different superscript letters are significantly different ($P<0.05$).

Table 3.10. Gross return to grower of winter wheat, winter canola, AWP and fallow from Year-1 of the winter rotation trials.

	2016	2017	Average
	-------------------- $ ha^{-1}	--------------------	
Winter wheat	$1,184 ^{b}	$1,811 ^{b}	$1,322 ^{b}
Winter canola	$1,906 ^{a}	$1,460 ^{a}	$1,859 ^{a}
AWP	$346 ^{c}	$132 ^{c}	$239 ^{c}
Fallow	$0 ^{c}	$0 ^{c}	$0 ^{c}
Average	$1,145	$1,134	$1,140

Based on commodity seed prices of $0.192 kg^{-1} for soft white wheat, $0.154 kg^{-1} for barley, $0.484 kg^{-1} for canola, and $0.276 kg^{-1} for pea and AWP.

Means assigned to different superscript letters are significantly different ($P<0.05$).

Table 3.11. Seed yield of winter wheat grown in Year-2 after winter wheat, winter canola, AWP, and fallow in Year-1 in the spring rotation trials.

Crop/Cultivar	2016	2017	Average
	-------------------- kg ha^{-1}		---------------------
Winter wheat	5,063 ^{b}	6,300 ^{b}	5,593 ^{b}
Winter canola	6,415 ^{a}	7,152 ^{ab}	6,731 ^{a}
AWP	6,655 ^{a}	7,527 ^{a}	7,029 ^{a}
Fallow	5,490 ^{b}	6,288 ^{b}	5,832 ^{b}
Average	6,817	5,906	6,296

Means assigned to different superscript letters are significantly different ($P<0.05$).

Table 3.12. Gross return to grower of winter wheat grown in Year-2 after winter wheat, winter canola, AWP, and fallow in Year-1 in the winter rotation trials.

	2016	2017	Average
	-------------------- \$ ha^{-1}		---------------------
Winter wheat	\$973 ^{b}	\$1,210 ^{b}	\$1,075 ^{b}
Winter canola	\$1,232 ^{a}	\$1,374 ^{ab}	\$1,293 ^{a}
AWP	\$1,278 ^{a}	\$1,446 ^{a}	\$1,350 ^{a}
Fallow	\$1,055 ^{b}	\$1,208 ^{b}	\$1,121 ^{b}
Average	\$1,310	\$1,135	\$1,210

Based on commodity seed prices of \$0.192 kg^{-1} for soft white wheat, \$0.154 kg^{-1} for barley, \$0.484 kg^{-1} for canola, and \$0.276 kg^{-1} for pea and AWP.
Means assigned to different superscript letters are significantly different ($P<0.05$).

Table 3.13. Means squares and significance levels from the analyses of variance of water infiltration and water seepage after harvest of winter wheat, winter canola, AWP, and fallow from Year-1 of the winter rotation trials.

Source of Variation	d.f.^{a}	Mean Squares Water infiltration		Water Seepage	
Year	1	7.9	ns	565.6	ns
Error (1)†	6	409.6	ns	3,580.3	ns
Crops	3	2,785.2	***	3,886.5	ns
Crops x Year	3	45.8	ns	5,068.7	*
Error (2)	29	157.5		1,464.7	
Model error (R^2)		53%		65%	

ns = not significant; * = 0.05>P>0.01, *** = P<0.001; † Error(1) = Rep *within* Years;
[a] Degrees of freedom

Table 3.14. Water infiltration and water seepage after harvest of winter wheat, winter canola, AWP, and fallow from Year-1 of the winter rotation trials. Data presented are averaged over two years of experimentation.

Crop/Cultivar	Water Infiltration		Water Seepage	
	- liters hour^{-1} -		-- cm^{-2} --	
Winter wheat	5.62	b	60.56	ab
Winter canola	27.03	a	44.89	b
AWP	7.46	b	49.69	b
Fallow	3.95	b	93.85	a
Average	11.02		62.25	
LSD 5%	13.18		40.20	

Means assigned to different superscript letters are significantly different (P<0.05).

Table 3.15. Average yield and gross return of spring rotation crops (spring wheat, spring barley, spring canola, and pea), subsequent yield and gross return from growing winter wheat following spring wheat, spring barley, spring canola, and pea, and two-year gross return of growing each of the 4 crop rotations.

	Crop Year		Winter Wheat Year		Two-Year Gross Return
Crop/Cultivar	Yield	Gross Return	Seed Yield	Gross Return	
	- kg ha^{-1} -	- \$ ha^{-1} -	- kg ha^{-1} -	- \$ ha^{-1} -	- \$ ha^{-1} -
Spring wheat	4,593 ^{b}	\$882 ^{b}	4,776 ^{a}	\$918 ^{a}	1,800 ^{b}
Spring barley	5,064 ^{a}	\$780 ^{c}	4,154 ^{b}	\$796 ^{b}	1,576 ^{c}
Spring canola	2,257 ^{c}	\$1,092 ^{a}	4,458 ^{ab}	\$857 ^{ab}	1,949 ^{a}
Spring pea	1,484 ^{d}	\$410 ^{d}	4,265 ^{ab}	\$819 ^{ab}	1,229 ^{d}
Average	3,350	\$791	4,413	\$848	1,639

Means assigned to different superscript letters are significantly different ($P<0.05$).

Table 3.16. Average yield and gross return of winter rotation crops (winter wheat, winter canola, AWP, and fallow), subsequent yield and gross return from growing winter wheat following winter wheat, winter canola, AWP, and fallow, and two-year gross return of growing each of the 4 crop rotations.

	Crop Year		Winter Wheat Year		Two-Year
Crop/Cultivar	Yield	Gross Return	Seed Yield	Gross Return	Gross Return
	- kg ha^{-1} -	- \$ ha^{-1} -	- kg ha^{-1} -	- \$ ha^{-1} -	- \$ ha^{-1} -
Winter wheat	6,881 ^{a}	\$1,322 ^{b}	5,593 ^{b}	\$1,075 ^{b}	2,397 ^{b}
Winter canola	3,841 ^{b}	\$1,859 ^{a}	6,731 ^{a}	\$1,293 ^{a}	3,152 ^{a}
AWP	867 ^{c}	\$239 ^{c}	7,029 ^{a}	\$1,350 ^{a}	1,589 ^{c}
Fallow	0 ^{c}	\$0 ^{c}	5,832 ^{b}	\$1,121 ^{b}	1,121 ^{c}
Average	3,863	\$1,140	6,296	\$1,210	\$2,065

Means assigned to different superscript letters are significantly different ($P<0.05$).

Chapter 4: Conclusions and Recommendations

Dryland PNW agriculture is dominated but small-grain cereals (mainly winter wheat) and there are few broadleaf crops that have sown agronomic or economic adaptability to the region. Highly intensive cereal production has several economic, disease, and weed problems that could threaten future farming sustainability. Winter and spring canola have shown good adaptability throughout the PNW and has higher yield potential than other US regions. However, in order for canola to have significantly greater hectarage base in the PNW it is necessary to quantify any rotation effects when grown with winter wheat. In addition, best management practices need to be determined to allow growers to maximize crop production and profitability.

This study addressed these two questions, being:

(1) What are the rotation benefits of winter and spring canola on following winter wheat crops?
(2) What are the optimum growing conditions to maximize winter canola production and grower returns?

4.1 Quantify Canola Rotation Effects

Compared to continuous wheat production, including either winter and spring canola both have beneficial effects on seed yield of winter wheat following. Compared to other possible rotation crops winter canola effects was markedly larger than spring canola.

In winter crop-winter wheat rotations, average grower gross returns were for winter canola (Year-1 of study), compared to either winter wheat or AWP. Compared to winter wheat in Year-1 winter canola gross return was over 40% higher.

Winter wheat yield following winter canola was slightly lower than winter wheat following AWP. However, winter wheat following winter canola out-yielded winter wheat following winter wheat by 1,138 kg ha^{-1} (~18 bu a^{-1}). Over the two-year rotation, gross returns of winter canola-winter wheat were \$3,152 ha^{-1}; being \$755 ha^{-1} (~\$314 a^{-1}) greater than winter wheat-winter wheat. When considering fallow periods necessary for winter canola, the per year return was \$147 ha^{-1} less than winter wheat. The comparability of success justifies further research because they are so similar. Winter canola yields should increase being planted on fallow (winter canola was planted into winter wheat in this study), thus, the per year return would increase. If the returns are statistically similar, winter canola should be included in rotations because of the advantage of better water infiltration and ability to break cereal weed/disease cycles.

The rotation benefit of including winter canola are still not clear. Including a broadleaf crop prior to winter wheat did not appear to reduce winter wheat foliar diseases. Stripe rust inoculum, for instance, is reintroduced to crops each spring regardless of previous crop. Soilborne disease (*Cephalosporium* stripe, *Rhizoctonia* root rot, Take-all) inoculum in cereal crop is impacted by the previous crop. However, it was notable that despite application of grass herbicides to all Year-2 winter wheat plots that grass weeds in the winter wheat following winter wheat were significantly increased. In addition, water infiltration rates following winter canola crops was 480% greater than following winter wheat. Furthermore, water seepage, as a metric of predicting water runoff, was 35% less in canola plots compared to wheat plots.

The rotational effects of including spring canola into winter wheat rotations was not as dramatic as that for including winter canola. In the spring crop-winter wheat rotation study highest seed yield was from the spring cereal crops but spring canola (having better commodity prices at harvest) resulted in greatest grower returns in Year-1 crops. Spring canola gross returns being \$1,092 ha^{-1} and spring wheat being \$882 ha^{-1}, or a 19% reduction in gross return.

Contrary to the winter crop-winter wheat results, winter wheat following spring wheat produced highest seed yield (918 kg ha^{-1} ~ 73 bu a^{-1}) and was 7% higher yielding than winter wheat following spring canola. Averaged over the two-year rotation, highest gross grower returns were from spring canola-winter wheat (\$1,949 ha^{-1}), followed by spring wheat-winter wheat (\$1,800 ha^{-1}). However, as spring canola did not show the positive effect on following winter wheat yields found following winter canola, then with different commodity crop prices a different result is likely, especially as wheat commodity prices were somewhat lower than those for canola at the time of this study.

In contrast to the winter-crop-winter canola rotations, there was little observed difference in grass weed infestation in winter wheat following any of the spring crops. The addition of spring weed control by cultivation or grass herbicides dulling the effects of including broadleaf crops prior to winter wheat. Spring canola crops are smaller in stature compared to winter canola and have a less aggressive taproot system. This was reflected in markedly lower water infiltration rates after spring canola, which although 2½ greater than spring wheat (on average), this was not statistically significant.

4.2 Best management practices for winter canola

To achieve best possible grower returns from winter canola, the crop should be grown as a forage and seed crops (i.e. dual-purpose crop). Forage yield was not significantly different over the four cultivars examined, but 18% higher forage yields were obtained when winter canola was planted at 50 cm row spacing compared to 25 cm row spacing.

Higher seed costs of HyC125W and Mercedes cultivars were not off-set by increased gross returns to growers when dual-purpose winter canola is produced. Averaged over years and sites gross grower returns on dual-purpose Amanda was \$2,760 ha^{-1}, WC15.7.5 was \$2,658 ha^{-1}, Mercedes was \$2,584 ha^{-1}, and HyC125W was \$2,427 ha^{-1}.

Cultivar and seeding rate significantly impacted seed yield of dual-purpose winter canola. Seed costs vary between different cultivars so optimized treatments are not based on which seeding rate yielded more canola seed. Mercedes and HyC125W had highest gross returns from planting at the lowest seeding rates (i.e. reducing seed input costs), while Amanda and WC15.7.5 had highest gross returns from the higher seeding rate.

Best management practices for growers who plant dual-purpose winter canola is to plant 5.6 kg ha^{-1} of Amanda seed between July and early August, at 50 cm row spacing. Most past research has shown than seed yield is equal or reduced when forage is harvested along with seed (Dann *et al*., 1977; Epplin *et al*., 2000; Epplin *et al*., 2001; Virgona *et al*., 2006; Kelman and Dove, 2009; Neely, 2010; Fransen, 2017). However, Amanda seed yield was increased after forage was harvested over no forage harvest, indicating that provided Amanda winter canola is planted between July and early August seed yields will not be negatively impacted by forage harvest. Farmers can plan to add forage biomass value to their predicted seed yields and expect the highest economic gains from using canola as a dual-purpose crop.

There will always be instances whereby growers do not to harvest forage from winter canola, either due to lack of suitable livestock, proximity to livestock, or simply as the additional harvest does not fit a suitable schedule. When winter canola is grown only for seed production then different best management practices must be applied. Averaged over all years and sites the highest yielding canola cultivar was Mercedes, and when only seed is harvested then the increased cost of Mercedes seed more than off-set the overall gross return of the crop.

Best management practices to maximize gross grower returns were to plant Mercedes at low seeding rates (~3.4 kg ha^{-1}) in late August-early September on wide row spacing.

4.3 Overall Conclusion and Recommendations

Synthesizing results from both experiments provides helpful information for PNW farmers when growing winter or spring canola. The first question farmers have to answer is which crop to plant? As winter wheat is the predominant PNW crop, then the question is which crop should be planted in rotation with winter wheat? The ‘best’ spring crop-winter wheat rotation had gross return of \$1,949 ha^{-1}, and the ‘best’ winter crop-winter wheat rotation had gross return of \$3,152 ha^{-1} over two grow years. In both cases, highest gross return was from rotations involving canola, so growers in the PNW should plant either winter or spring canola in rotation with winter wheat. Given that the rotational advantages of winter canola far exceed those of spring canola, perhaps a better recommendation would be that growers should grow winter canola (where possible or feasible) in rotation with winter wheat.

The next question farmers must answer is: what are the best management practices that will optimize economic return of winter canola. To address this, it is first necessary to ask whether there is a potential near-farm use for canola forage. If yes, then Dual-purpose winter canola will produce 'best' gross returns, by planting Amanda at a high seeding rate (~5.6 kg ha^{-1}) in July or early August with a wide row spacing and harvest forage around late September early October. If canola forage is not required, then best management practices to maximize gross grower returns were to plant Mercedes at low seeding rates (~3.4 kg ha^{-1}) in late August-early September on wide row spacing.

Overall, agronomic studies showed that earlier planting and wide row spacing produce 'best' results. Also, rotation advantages of winter canola prior to winter wheat were marked in these trials. However, in these rotation trials winter canola was always planted late, with narrow row spacing and at high seeding rates. It would be appropriate to examine winter canola-winter wheat rotation experiments where the winter canola is planted under different managements to determine the impacts of these agronomies on following winter wheat productivity.

4.4 References

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