EXAMINING THE AGRONOMIC AND ECONOMIC FEASIBILITY OF UTILIZING WINTER AND SPRING BRASSICACEAE OILSEED CROPS (*BRASSICA NAPUS*, *B. RAPA*, *B. JUNCEA*, *B. CARINATA*, *SINAPIS ALBA*, AND *CAMELINA SATIVA*) FOR BIOFUEL FEEDSTOCK PRODUCTION IN THE INLAND PACIFIC NORTHWEST

A Thesis

Presented in Partial Fulfilment of the Requirements for the

Degree of Master of Science

with a

Major in Plant Science

in the

College of Graduate Studies

University of Idaho

By

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December 2015

Authorization to Submit Thesis

This thesis of Pedee James Ewing, submitted for the degree of Master of Science with a Major in Plant Science and titled "Examining the agronomic and economic feasibility of utilizing winter and spring Brassicaceae oilseed crops (*Brassica napus, B. rapa, B. juncea, B. carinata*, *Sinapis alba*, and *Camelina sativa*) for biofuel feedstock production in the inland Pacific Northwest" has been reviewed in final form. Permission, as indicated by the signatures an dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

The United States is highly dependent on fossil fuel, which has heightened interest in producing biofuel from vegetable oils. Brassicaceae oilseed crops have potential as rotational crops with small grain cereals that predominate in the Pacific Northwest. However, few studies have determined productivity of these crops in side-by-side comparisons. This study examines adaptability, seed yield and oil content of three fall planted and six spring planted Brassicaceae species to assess their biofuel feedstock potential, grown in rotations with winter wheat. Results showed the highest fuel feedstock potential was from winter *B. napus*, spring *B. napus*, and *B. juncea* (1,800, 795, and 636 l ha^{-1}, respectively). There were no difference in subsequent wheat yield or quality after any of the oilseed crops. To produce Brassicaceae biofuel feedstock crops, the recommendation is to produce winter *B. napus* in the crop-fallow regions, and spring *B. napus* or *B. juncea* in continuous cropping systems.

Acknowledgments

I would like to thank my advisor Jack Brown for all of his help and support, I would not be able to do this without his guidance and wisdom and patience. Additionally the University of Idaho Canola, Rapeseed & Mustard Breeding group has helped me along this journey. Jim Davis for his attention to detail and great perspective and intelligence. Additionally Megan Wingerson, Bradley Pakish, Sage McClintick-Friddle, Kate Reed, James Ihli, Samantha Wright, and Bailie Luna for all their help.

I owe a great deal of gratitude to my graduate committee: Kurt Schroeder and Joe Kuhl for their support.

I would not be where I am without the unconditional support from my mom Christine Ewing, my father Dan Ewing Sr. and all of my family. They have been a cornerstone on my foundation with their love and advice. Finally I would like to thank Sarah Herberger for her support, understanding, and love.

Dedication

This thesis is dedicated to everyone furthering their education, because no one can ever take away what you have learned.

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Chapter 1: Introduction

The United States uses a substantial amount of fossil fuel as an energy source for a wide range for functions from home heating, agriculture and transportation. Liquid fuel in the form of diesel, jet fuel, and gasoline are being consumed at a rapidly.

Alternative energy is being investigated globally, and nationally. Countries around the world have passed mandatory biofuel production legislation to shift dependence from fossil fuel and mitigate impact on the climate. Continuing to investigate biofuel feedstock crops such as Brassicaceae oilseeds, is helping break dependence on fossil fuels.

The Palouse region of the inland Pacific Northwest (PNW) consists of 1.3 Million hectares (M ha) of dry land-farming stretching over northern Idaho and eastern Washington and into Oregon. Of this, winter wheat occupies a substantial amount of all planted hectares.

Winter wheat traditionally provides the greatest economic return and consistent performance, its high yield potential creates a monetary incentive to growers to produce wheat on the majority of this available land.

Monoculture production of crops is not sustainable and can have negative economic and environmental impacts. Traditional long-term wheat-fallow production systems can leave soils susceptible to erosion and reduce soil health. In addition, cropping systems with a predominance of small grain cereals increases grassy weeds, soil borne disease and pests, and can lead to reduced yield.

Alternative crop options and well developed rotations are important for sustainable agriculture. Selecting appropriate equipment for field operations, adopting sustainable management strategies, and adding a diversified crop rotation that includes broadleaf plants can be advantageous for growers both agronomically and economically. Growers often choose to take advantage of spring crops because they use different management cycle and can perform management of weeds.

The inclusion of Brassicaceae crops in rotation with small grain cereals have shown positive effects on subsequent wheat yields, quality, and disease incidence depending on environmental conditions and merit greater investigation. In addition Brassicaceae crops produce high biomass that reduces soil erosion and can increase soil organic matter. Deep penetrating tap root systems can break up soil panning, and allow better water infiltration.

However, Brassicaceae crops (i.e. canola, rapeseed, and mustard), are more recent introductions in the PNW and other potential Brassicaceae crops (i.e. Ethiopian mustard and Camelina) have yet to be fully investigated. Understanding the impact of Brassicaceae crop on subsequent winter wheat productivity will also give perspective and understanding for making better management decisions.

This project examines fall and spring planted Brassicaceae crops to better understand their adaptability, productivity, and potential as biofuel feedstocks in the PNW. Characteristics examined include, crop establishment and seedling survival, leaf area index (spring crops only), seed yield, seed oil content, oil yield, and subsequent wheat yield and quality.

The specific objectives of this research include:

- Examine four winter *B. napus*, one winter *B. rapa* and one winter *C. sativa* oilseed cultivars to determine which cultivar(s) have the best potential as oil feedstock crops in the PNW.

- Examine two spring *Brassica carinata*, two spring *B. juncea*, four spring *B. napus*, one spring *B. rapa* and one *C. sativa* oilseed cultivars to determine which cultivar(s) have the best potential as oil feedstock crops in the PNW annual cropping regions.
- Examine differential rotational impact of these winter and spring Brassicaceae oilseed crops on subsequent winter wheat production.

Chapter 2: Examining the potential of utilizing winter oilseed Brassicaceae crops (*Brassica napus* L., *B. rapa* L., and *Camelina sativa* L.) as viable biofuel feedstock crops in rotation with small grain cereals in the Pacific Northwest region.

2.1 Abstract

The United States (U.S.) uses a substantial amount of fossil fuel as an energy source, billions of liters are consumed each year. Liquid energy resources will continue to be an issue, as well as have a lasting negative environmental impact, for future generations. Alternative energy is being investigated nationally, and globally including sixty-two countries. There are clear environmental, economical, and societal justifications that are driving the need for alternative fuel sources and hence alleviate the unconstrained use of fossil fuel. Brassicaceae oilseed crops have potential as alternative crops for use as biofuel feedstock crops for production of biofuels and have been grown for their seed oils for thousands of years. *Brassica napus, B. rapa,* and *Camelina sativa* are of particular interest for the Pacific Northwest. The objective of this research was to determine which fall planted Brassicaceae oilseed crop species had the greatest potential as oilseed feedstock crops in regards to their performance. Field trials were planted at two locations (Moscow and Genesee, in northern Idaho) in the fall of 2012, 2013 and 2014. Two *B. napus* winter canola quality cultivars (‘Amanda’ and ‘Wichita’), two *B. napus* rapeseed quality cultivars (‘Durola’ and ‘Dwarf Essex’), one *B. rapa winter* canola cultivar (‘Largo’), and one cold-tolerant *C. sativa* cultivar ('Joelle’) with fall planting potential, were examined. Wichita showed the highest potential in terms of yield with an overall average of 3,658 kg ha^{-1}, and with good seed oil content (413.1 g kg^{-1}), producing over 1,800 l ha^{-1} of feedstock oil.

Amanda also performed consistently with high seed yield and oil content and better winter tolerance. *Brassica rapa* cultivar Largo had an average yield of 1,852 kg-ha^{-1} and was lower yielding than any of the *B. napus* cultivars. Joelle (*C. sativa*) had the lowest seed yield, seed oil content, oil yield and was most intolerant to winter damage, at times resulting in total crop failure or loss, and may not be a wise choice for production.

2.2 Introduction

2.2.1 *Current energy situation*

The U.S. uses a substantial amount of fossil fuel as an energy source for a wide range for functions from home heating, agriculture and transportation. The U.S. Energy Information Administration (USEIA) reported in 2014 that 219.96 billion liters (58.11 billion gallons) of diesel fuel and an additional 517.77 billion liters (136.78 billion gallons) of gasoline were consumed in the U.S. In 2014, an average of 602 million liters of diesel fuel and 1,419 million liter of gasoline (159 million and 375 million gallons, respectively) were used in the US every day (USEIA, 2015a; USEIA, 2015b). Refineries in the U.S. produced an average of 45 liter (12 gallons) of diesel fuel and 72 liter (19 gallons) of gasoline from one 42 gallon barrel (159 liter) of crude oil (USEIA, 2015c). In addition, the U.S. consumed 830 billion liters (220 billion gallons) of jet fuel in 2013 (USEIA, 2014).

All trends examined indicate that U.S. fossil fuel consumption will either rise or at best remain constant in the future. Therefore liquid energy resources will continue to be an issue of economic consideration as well as have a lasting environmental impact on future generations.

The importation of crude oil into the U.S. has been in decline since 2006 with exports picking up around the same time (Figure 2.1). The U.S. imported 9 million barrels day^{-1} (MMbbl d^{-1}) of petroleum in 2015 from over 80 different countries, the top five being Canada, Saudi Arabia, Mexico, Venezuela, and Iraq (USEIA, 2015d). The global energy industry will continue to change and political and economic ramifications are felt by any individual that uses related products or travels.

At the current rate of use the U.S. Energy Information Agency (U.S.EIA) currently projects the world's fossil fuel resources to last only until 2040. Optimistic predictions believe that this will be enough time for alternative fuel technology's to become more efficient and widespread. Even the most optimistic forecasts point to multiple alternative fuel options to fit our future needs. Biofuels could help with stability in price and availability of fuel resources; if we are producing more here we rely less on others and work towards energy security that is important to the U.S. economy.

2.2.2 *Alternative energy is needed*

Alternative energy is being investigated globally, and nationally. Sixty-two countries around the world have made mandatory biofuel production legislation to shift dependence from fossil fuel sources (Lane, 2014). The Energy Independence and Security Act of 2007, mandated improvements on existing vehicle technology, and works to improve the environment through reduced emissions and achieve more energy security through the production of biofuels (Energy Independence and Security Act of 2007). The National Aeronautics and Space Administration (NASA), and National Oceanic and Atmospheric Administration (NOAA) are amongst the myriad of agencies providing unequivocal, empirical evidence of climate change.

There are clear environmental, economical, and societal justifications that are driving the need for alternative fuel sources and hence alleviate the constant use of fossil fuel.

There has been renewed interest in familiar forms of alternative energy such as solar, nuclear, hydroelectric and wind. It should be noted that these technologies have made considerable advances in efficiency, and yet each offer their own unique challenges and solutions to our energy needs. Additional possibilities include geothermal, methane and waste product feedstock's tidal energy, and hydro kinetic and other ocean based energy sources (Black & Flarend, 2010). While all of these options provide energy diversity, there are issues with placement of these options due to the nature of their energy production and the infrastructure required for their use. In addition all of these alternative energy options produce electricity and not the convenient liquid fuels needed for many forms of transportation. Indeed currently only bioethanol, biodiesel, and bio-jet fuel offer "drop in" alternatives to petroleum based fuels that require little or no additional mechanical modifications to engines. It is difficult to foresee a future whereby airplanes become powered by nuclear energy or indeed electricity!

2.2.3 *Brassicas are of particular interest*

Although biodiesel and bio-jet fuel can be made from any vegetable or animal fats, few oilseed crops have shown good adaptability to environments that exist in the Pacific Northwest (PNW) region. Brassicaceae oilseed crops have potential as alternative crops for use as feedstock crops for production of biofuels (Schillinger & Papendick, 2008). Brassicaceae crops have been grown for their seed oils for thousands of years. Cultivation across Europe was first intended for use as lamp oil (McNaughton, 1988). More recent food and industrial use demand has increased Brassicaceae oilseed crop acreage, and crops have been genetically improved and adapted with simultaneous improvements in agronomics, and processing technology, leading to higher yields (Booth & Gunstone, 2004).

From 2013 to 2015 producers in the U.S. planted 545,516; 693,631; and 628,881; hectares (ha), of canola respectively, mainly *Brassica napus* (USDA, NASS 2015). North Dakota had the most substantial portion of 485,622 ha in 2015, followed by Oklahoma with 58,680 ha and Montana with 24,281 ha (USDA, NASS 2015). Idaho in 2014 had planted 14,164 ha. Interest in non-food Brassicaceae oils has generated greater interest in producing rapeseed (*B. napus* and *B. rapa*), mustards (*B. juncea*, *B. carinata,* and *Sinapis alba*) and camelina (*Camelina sativa*) in the PNW region (Cardone *et al.*, 2002; Fröhlich & Rice, 2005; Jahm *et al.*, 2009; Manco, 2009; Shonnard *et al.*, 2010; Ciubota-Rosie *et al*., 2013; Sanjid *et al.*, 2014).

2.2.4 *Current PNW agriculture*

Winter wheat has an extensive history in the PNW and has typically been a very profitable and productive crop for growers over the lasted 125 years (Schillinger *et al.*, 2006; Schillinger & Papendick, 2008). Lack of adapted alternative crops to grow in rotation with winter and spring wheat has led to a predominantly small grain cereal production system. PNW wheat growers have experienced problems with cereal disease, sever water and wind erosion, increased weed and pest problems, and reduced crop yields in cropping systems predominated by winter and spring wheat (Bewick *et al.*, 2008; Schillinger & Papendick,. 2008). Continuous wheat production has led to problems with grassy weeds (Schillinger *et al.*, 2006; Schillinger & Papendick, 2008). Introduction of Brassicaceae oilseed crops into wheat rotations can increase yield in subsequent grain crops (Scarisbrick *et al.*, 1986; Bourgeois & Entz, 1996). These crops have similar water use efficiencies when compared to wheat (Hocking *et al.*, 1997), can reduce weed infestations (Liebman & Dyck, 1993) and disease pressures (Krupinsky *et al.*, 2004).

2.2.5 *Potential fall planted Brassicaceae oilseed species*

2.2.5.1 *Brassica napus*

Brassica napus is the amphidiploid result of a cross between *B. rapa* and *B. oleracea* (Scarisbrick *et al.*, 1986). *Brassica napus* also known historically as "Argentine rape", "Rapeseed", "Oilseed Rape" or more recently "Canola", is the most commonly grown Oilseed Brassicaceae crops in Europe, Canada and China (Booth & Gunstone, 2004). Winter and spring types of *B. napus* are available; however, winter types have a higher yield potential in favorable growing conditions and are often preferred for this reason (Booth & Gunstone, 2004).

Brassica napus is grown for either rapeseed or canola quality seed oils. Rapeseed oil refers to the industrial form of oil derived from *Brassica* species. Rapeseed cultivars are cultivars that have high concentrations of erucic acid, a 22 carbon fatty acid with a single double bond in the seed oil. Older rapeseed cultivars (i.e. see 'Dwarf Essex' below) can have high glucosinolate content in the seed meal; although all newer cultivars have low glucosinolate content (i.e., comparable to canola with less than 30 µmoles of total glucosinolate per gram of defatted seed meal). Canola oil refers to the edible form of oil, produced by *Brassica napus* or *B. rapa*. This definition is in compliance with the Canadian standard where the oil must contain less than 2% erucic acid and where the residual meal contains less than 30 µmoles of total glucosinolate per gram of defatted meal. In the past few years a mustard species (*B. juncea*) have been modified to produce the same oil profile and meal quality as canola and in the future other cultivars also may be considered as canola species.

Brassica napus has dark bluish green foliage, smooth and partially clasping leafs around the stems. The stems branch, though the amount depends on cultivar and environment. The flowers are yellow, clustered at the top but not higher than the terminal buds, and open upwards from the base of the raceme (CFIA, 2012). The University of Idaho has brought considerable genetic and agronomic improvement to *B. napus* cultivars over the last 35 years.

2.2.5.2 *Brassica rapa*

Early history regarding the evolution of Brassicaceae oilseed species can be difficult to differentiate as those of *B. rapa* and *B. napus* have shared so much in common. It is certain that *B. rapa* must have originated before its progeny *B. napus* (Scarisbrick *et al.*, 1986). *Brassica rapa* also known as “turnip rape” or “Polish rape” accounts for a large portion of western Canadian production because of its earlier maturity and good cold tolerance (Booth, & Gunstone, 2004).

The biology and physiology of *B. rapa* is similar to *B. napus*, although the former is earlier maturing, albeit lower yielding, yet may be advantageous for certain growing conditions. Additionally *B. rapa* tends to have better seed shatter resistance. It is similar to *B. napus* with green foliage, height, and structure. However, *B. rapa* tends to have more serration and hairs on its leaves.

2.2.5.3 *Camelina. sativa*

Evidence of the origin and early evolution of *C. sativa* is believed to be from Eastern Europe (Ghamkhar *et al.*, 2010; Eynck & Falk, 2013). It is thought to have been an invasive pest to early flax crops and later grown as a crop across Russia and Europe. Production waned through the middle ages as other oil crops had become more common (Eynck & Falk, 2013). Russia and the Ukrainian regions are especially considered to be areas of development for *C. sativa* (Ghamkhar *et al.*, 2010). Interest in *C. sativa* increased as it was re-introduced as a weed a second time, in the development of the New World and was later praised for its tenacity as a low input oil crop (Eynck & Falk, 2013). Recent interest in this species for its use as a non-food biofuel feedstock crop, for producing bio jet fuel that fits neatly in rotation with winter wheat (Shonnard *et al.*, 2010).

Camelina sativa, is a short season crop, typically a summer annual, but can also be planted in the fall in the PNW. It has been noted as a low fertility input crop with a unique oil profile with potential for use in food, industrial uses, and biofuels (Hulbert *et al.,* 2012). Rosette leafs are not lobed, the pear-shaped silicles are smooth and contain 5-15 gold to brown very small seeds. It has been regarded as having good cold weather tolerance and the ability to go through several freeze thaw cycles and still perform as a crop (Eynck & Falk, 2013).

2.2.6 *Research objectives*

The objective of this research was to determine which fall planted Brassicaceae oilseed crop species had the greatest potential as oilseed feedstock crops in regards to their performance.

Specific objectives of this research are:

- Examine four *B. napus,* one *B. rapa* and one *C. sativa* oilseed cultivars to determine what cultivar(s) have the best potential as oil feedstock crops.
- Examine differential rotational impact of these fall-planted Brassicacea oilseed crops on subsequent winter wheat (discussed in Chapter 4).

2.3 Materials and Methods

2.3.1 *Site and trial specifications*

Field trials were planted at two locations in northern Idaho (Moscow and Genesee) in the fall of 2012, 2013 and 2014. The University of Idaho Parker Research Farm, Moscow, ID

(46°43’N 116°57’W) has an average yearly precipitation of 55 cm and is a Palouse silt loam soil type with a 0-3% slope. The University of Idaho Kambitsch Research Farm, Genesee, ID (46°55’N, 116°92’W) has a yearly precipitation of 45 cm and is a Naff Palouse silt loam, a common soil type throughout the region.

Individual plot dimensions at Moscow and Genesee in 2012-2013 and 2013-2014 were 5.89 m x 4.57 m, and 3.07 m x 8.00 m in the 2014-2015 season. Seed was planted at Moscow on September 14th 2012, August 12th 2013 and September 3rd 2014. Seed was planted at Genesee August 16th 2013, and September 2nd 2014.

The Moscow sites received 358 kg ha^{-1} (320 lbs a^{-1}) of 31-10-0-7(N-P_2O_5-K_2O-S), which is a 50:50 blend by weight of pelletized urea {CH_4N_2O} (46-0-0-0) and pelletized ammonium phosphate-sulfate {$H_4NO_8PS_{-4}$} (16-20-0-15). The result was 111 kg ha^{-1} (99 lbs a^{-1}) of N , 36 kg ha^{-1} (32 lbs a^{-1}) of P_2O_5 , and 27 kg ha^{-1} (24 lbs a^{-1}) of S fertilizer applied and incorporated into the soil prior to planting.

The Genesee sites received a blend of anhydrous ammonia (82-0-0-0), Thio-Sul® (12-0-0-26), and liquid ammonium phosphate (11-37-0-0) applied before planting and below the soil surface with a McGregor Co. "ripper-shooter" applicator leaving 112 kg ha^{-1} (100 lbs a^{-}1) N, 11 kg ha^{-1} (10 lbs a^{-}1) P_2O_5, and 22 kg ha^{-1} (20 lbs a^{-1}) S .

All trials were planted into mechanical summer-fallow ground and the crop prior to fallow at each year and site was spring barley. Prior to the fallow year the ground was chisel plowed in the preceding fall. Throughout the fallow year weeds were controlled through 2-3 harrow operations and prior to planting Trifluralin (α,α,α-Trifluoro-2, 6-dinitro-N, N-dipropyl-p-toluidine) herbicide was pre-plant incorporated to a depth of 10 cm at a rate of 2.33 l ha^{-1}.

All trials were planted with a single cone, double disc opener plot planter, planting 6 rows 13 cm apart and each plot was planted as 3 individual separate passes of the plot planter for the first 2012-2013 year and later as 3 passes of the plot planter combined into one plot. All *B. napus* and *B. rapa* seed was treated with Helix Xtra™ (thlamethoxam, difenoconazale, mefenoxam, fludioxonil) at a rate of 15 mL kg^{-1} seed to control fungal diseases and early season insects. *Camelina sativa* seed was not treated prior to planting. Planting depth was uniform across individual trials and was adjusted at each trial to the appropriate moisture depth (7-13 cm), depending on the individual site year's soil moisture level.

After emergence, weeds were controlled through hand-weeding where necessary. Plots were routinely inspected for insect infestation and when Cabbage aphids (*Brevicoryne brassicae*) or flea beetles (*Psylliodes cruciferae*) observed they were controlled with foliar application of Warrior II (Lambda-cyphalothrin) insecticide (Syngenta, 2014).

2.3.2 *Cultivars examined*

We examined two species of fall planted *Brassica* (*B. napus* and *B. rapa*) and one fall planted *Camelina* each year from 2012-2015. The four *B. napus* cultivars and one *B. rapa* and one *C. sativa* were suggested as representatives for their species. Two *B. napus* winter canola cultivars (Amanda and Wichita), two *B. napus* rapeseed cultivars (Durola and Dwarf Essex), one *B. rapa winter* canola cultivar (Largo), and one cold-tolerant *C. sativa* cultivar (Joelle) with fall planting potential, were examined.

Amanda (PVP 201100403) canola (Brown *et al.*, 2008) and Durola (PVP 201300085) rapeseed were both developed at the University of Idaho. Dwarf Essex (PI.11165) is an older (land race) cultivar often used as a control for comparison with newer winter oilseed cultivars. Wichita (PI.612846) was released in 1999 by the Kansas Agricultural Experimental Station at Kansas State University (Rife & Shroyer, 2000). *Brassica rapa* canola cultivar Largo was developed as a selection from the older cultivar 'Salute' by SW Seed, Sweden and released in 2002. *Camelina sativa* cultivar Joelle was selected from a germplasm collection at Montana State University and has shown potential for fall planting.

2.3.3 *Experimental design*

The experimental design was a randomized complete block with 4 replicates of 6 cultivars from 3 species. This design was repeated at one location in 2012-2013 and two locations in 2013-2014 and 2014-2015.

2.3.4 *Data collected*

Plant stand was recorded when plants had reached the 5 to 6 leaf stage, by counting the number of plants per linear meter. Counts were taken from the center of the plot to avoid edge effects.

Winter kill was visually assessed each spring on a 1 to 9 scale with 9 being no winter damage and 1 being complete crop failure. Winter damage was slight in 2012-2013 and 2013-2014 but severe in 2014-2015 when extensive winter kill was observed. Days from January 1st to 50% flower bloom was recorded. Plant height was recorded after flower ending and after the onset of pods (term we use for silique), and before full maturity. Pod characteristics were recorded by cutting three main racemes from each plot, and counting pods on each raceme. Thereafter five representative pods were opened to determine the number of seed pod^{-1}. Lodging was evaluated visually on a 1 to 9 scale with 9 being no lodging.

Prior to full maturity plants were swathed with a plot swather at upon 50% of the seeds on the plants were brown. After swathing and drying all plots were harvested using a Wintersteiger Classic™ (Wintersteiger, Inc.; Salt Lake City, UT) small plot combine. Recommended combine settings for small-seeded oil crops were used for the *B. napus* and *B. rapa* cultivars. However, settings with *C. sativa* plots were adjusted to allow poor seed-chaff separation by air. Harvested seed was air-dried at 50° C for 2 days and was weighed to determine each individual plots yield. *Camelina sativa* harvested samples contained high chaff levels and were hand cleaned by sieves before its weight was determined. Sub-samples of seed were taken from each plot to determine see oil content. Oil content was determined on single 12 g samples following the procedures outlined by Hammond (1991) using a Newport MKIIIA Nuclear Magnetic Resonance (NMR) Analyzer (Oxford Instruments Inc., Concord, MA). The NMR was calibrated with a single reference sample of known oil content of the appropriate species and the sample analysis carried out as described by Howard and Daun (1991). Oil yield was determined by calculating l ha^{-1} (gal a^{-1}) equivalent from seed yield and seed oil content.

2.3.5 *Data analysis*

Data was analyzed using a general linear model analyses of variance and Duncan's multiple range tests. All computations were carried out using the Statistical Analysis Software (SAS, 2009).

2.4 Results

Means squares from the analyses of variance of seedling stand, seedling survival, crop establishment, plant height, lodging, and 50% bloom date are presented in Table 2.2. Means squares from the analyses of variance of yield, oil content, oil yield, number of pods, and seeds per pod are presented in Table 2.3.

It is clear from Tables 2.2 and Table 2.3 that year differences were highly significant for all pre-harvest and post-harvest variables. Differences between sites was significant for winter kill, seedling establishment, plant height, 50% bloom date, seed yield, oil content, oil yield, number of pods and seeds pod^{-1}. Site x year interactions were significant for winter kill, seedling establishment, plant height, days to 50% bloom, and oil content.

In this study, the greatest interest is with regard to differences between cultivars, and cultivar differences were significant for all variables examined. Cultivar x site interactions were also significant for all variables examined, with the exception of seed oil content and seeds pod^{-1}. Significant cultivar x year interaction were observed for winter kill, seedling survival, plant height, 50% bloom date, but not significant for any of the post-harvest traits. The three-way interaction between cultivar x site x year was significant for seedling survival and plant height. It should be noted that most cultivar interaction effects were small in comparison to the main effects of cultivars and in most of the cases the cultivar interactions were scalar and did not have major changes in cultivar rankings.

2.4.1 Pre-harvest traits

Amanda showed greater winter-hardiness than the other three *B. napus* cultivars (Table 2.4). Amanda also produced high stands, excellent seedling survival, and crop establishment, was moderately tall and reached 50% flower bloom later than the other *B. napus* (132 days from January 1^{st}). Durola also had good winter hardiness, and showed the best crop establishment. Dwarf Essex had moderate winter hardiness, excellent seedling stand and seed survival, had tall plant stature and moderate flowering date. Wichita was most susceptible to winter damage, had lower stand counts, and moderate seedling survival and crop establishment, with tall plant stature (144 cm), and late flowering. Largo (*B. rapa*) showed good winter hardiness good seedling stand and survival tall stature and very early flower bloom date. Joelle (*C. sativa*) had markedly greater winter damage, and showed 100% winter-kill in some years. Joelle also had lowest seedling stand counts, seedling survival, crop establishment, shortest plant height, and earliest flower start date.

2.4.2 Yield components

The highest seed yield was achieved from the *B. napus* winter canola cultivar, Wichita (3,658 kg ha^{-1}), followed by Amanda (3,252 kg ha^{-1}), which was not significantly higher yielding than Durola (2,965 kg ha^{-1}) (Table 2.5). The older *B. napus* cultivar Dwarf Essex was significantly lower yielding than the other *B. napus* cultivars, show that genetic gains have been achieved by recent breeding efforts. Largo seed yield was significantly lower than all *B. napus* cultivars and Joelle (*C. sativa*) had the lowest yield (1,148 kg ha^{-1}), less than one third of the seed yield obtained from Wichita. The highest seed oil content was obtained from *B. napus* (445.7 g kg^{-1}) compared to *B. rapa* (398 g kg^{-1}) or the lowest oil content *C. sativa* (344 g kg^{-1}). Durola produced significantly higher seed oil content (446 g kg^{-1}) than the other three *B. napus* cultivars.

Oil yield ha^{-1} is a good indicator of biofuel feedstock producing potential. It is apparent that high oil yield will indicate the potential volume of biofuel that could be produced in a region. Oil yield was calculated by simply multiplying seed yield by the percentage of seed oil (Table 2.5). The highest oil yield was obtained from the three *B. napus* cultivars, Wichita (1,805 l ha^{-1}), Amanda (1,627 l ha^{-1}), and Durola (1,599 l ha^{-1}). Dwarf Essex oil yield was lower, but still significantly higher than that obtained from Largo, and Joelle had lower oil yield, producing only 493 l ha^{-1}, almost ¼ of that possible from winter *B. napus*.

Higher seed yield of Wichita and Amanda was achieved through having more seeds pod^{-1} compared to the two rapeseed lines (Table 2.5). Amanda produced significantly more pods $raceme^{-1}$ than the other *B. napus* cultivars, including Wichita, suggesting that the high yield for Wichita also resulted from larger seed size. Comparison of seeds pod^{-1} and pods $raceme^{-1}$ suggest that all the *B. napus* cultivars had larger seed size compared to Largo (*B. rapa*). Joelle produced the highest number of pods $raceme^{-1}$, but significantly fewer seeds pod^{-1}. Of course Joelle produces significantly smaller seeds compared to all other cultivars under examination.

2.5 Conclusions and Recommendations

For a crop to be considered a potential candidate for producing biofuel feedstock it must combine high yield and high seed oil content. Oil yield will ultimately determine the potential biofuel producing capacity, but this must combine high seed yield to ensure growers are suitably compensated for producing the crops. Additionally these crops must have adaptability and agronomic support in addition to the infrastructure needed for its production.

From the three oilseed species examined here, it was clear that *B. napus* cultivars show clear advantages in all of the variables examined over either *B. rapa* or *C. sativa* as fall-seeded crops.

Based on this research *B. napus* winter canola cultivar Wichita showed the highest potential in terms of yield with an overall average of 3,658 kg ha^{-1}, and with good seed oil content (413.1 g kg^{-1}), producing over 1,800 l ha^{-1} of feedstock oil. Amanda winter canola also performed consistently with high seed yield and oil content. Amanda has been developed to be adapted to the PNW environment and local growers are already familiar with this variety. In addition Amanda had better winter-hardiness than that Wichita, which may offer better long-term stability over years. Additionally Amanda was 10 cm shorter than Wichita, and the lower plant biomass may make it an easier crop for growers to harvest.

The highest oil content was from the winter rapeseed cultivar Durola (445 g kg^{-1}), and although it was lower in seed yield than the two canola cultivars, produced an oil yield (1,599 l ha^{-1}) that was not significantly different. The longer carbon esters of industrial rapeseed (erucic acid, 22:1 compared to oleic acid, 18:1) will usually results in higher oil content. Greater breeding efforts into rapeseed development may over time address the reduction in seed yield compared to canola and hence increase feedstock production potential in the future.

Brassica rapa cultivar Largo had an average yield of 1,852 kg-ha^{-1} and was lower yielding than all of the *B. napus* cultivars. Early maturity and resistance to seed pod shatter may give this cultivar/species greater potential over *B. napus* (i.e. in the hotter drier regions of the PNW). However, results from recent PNW Winter Canola Variety Trials (Davis *et al.*, 2013; 2014; 2015) show that *B. rapa* yield potential throughout the region are generally reduced and hence the overall feedstock potential for *B. rapa* must be lower than that for *B. napus*. Joelle (*C. sativa*) had the lowest seed yield, seed oil content, lowest oil yield and was most intolerant to winter damage, at times resulting in total crop failure or loss. Joelle did produce competitive yield at Genesee in 2013-2014 (2,166 kg ha^{-1}); however, winter conditions that season were not particularly severe. Lack of stability of performance of Joelle would make it an unwise choice to base a biofuel industry, where stable yields will be necessary. This is in contrast to other findings suggesting it can be grown as a winter annual crop in the PNW (Hulbert *et al.*, 2012).

Future breeding research will likely continue to produce genetically superior cultivars with better adaptability for commercial production. Breeding for higher yield and oil content, oil quality, and disease and insect resistance will most likely be necessary to meet challenges ahead. Additional grower resources and marketing will be essential to productive and widespread oil feedstock production in the Pacific Northwest.

A large proportion of dry land agriculture in the PNW is dominated by winter wheat and few alternative crops are available that have adaptability or profitability potential. The overall conclusion of this research is that winter canola and winter rapeseed showed high yield and high biofuel feedstock potential with over 1,800 l ha^{-1} (~201 gal $acre^{-1}$), which is greater than most other oilseed crops available. Current canola and rapeseed seed prices fluctuate continually but on November 1st were \$0.396 kg^{-1} and \$0.440 kg^{-1}, respectively. This would potentially return \$1,448 ha^{-1} and \$1,305 ha^{-1}, respectively to growers growing winter canola or rapeseed, respectively, and is highly competitive with winter wheat in today's market. Additional, rotational benefits of including these crops in rotation with winter wheat may increase the value of them and the sustainability of PNW agriculture.

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Table 2.1. Developer and end-use oil product of six Brassicaceae crop cultivars from three species.

Species	Cultivar	Developer	End-use product
B. napus	Amanda	University of Idaho	Edible oil
	Durola	University of Idaho	Industrial
	Dwarf Essex	Land Race	Industrial
	Wichita	Kansas State University	Edible oil
B. rapa	Largo	SW Seed Sweden	Industrial
C. sativa	Joelle	Montana State University	Industrial

Table 2.2 Means squares from the analysis of variance of crop establishment, seedling stand, seedling survival, days from January 1^{st} to 50% flower bloom, plant height, and lodging from six cultivars planted at two locations over three years and four replicates.

Source	[a]d.f.	Establishment	Seedling Stand x 10^{-6}	Seedling Survival	Winter kill	Plant Height	50% Flower Bloom
Year	2	62.47 ***	1,487,849 ***	10,094 ***	287.92 ***	1,423 ***	10,000.69 ***
Error (1)†	9	1.49 ***	7,336 n.s.	36 n.s.	0.2 n.s.	104 *	2.45 **
Site	1	13.12 ***	505 n.s.	4 n.s.	27.55 ***	213 *	191.43 ***
Site*Year	1	14.93 ***	2,079 n.s.	14 n.s.	3.75 ***	7,635 ***	126.45 ***
Error(2)†	4	2.02 **	5,678 n.s.	34 n.s.	0.45 n.s.	156 *	0.17 n.s.
CV	5	3.82 ***	123,972 ***	1,630 ***	0.43 *	4,194 ***	31.13 ***
CV*Site	10	3.87 ***	55,125 ***	415 ***	11.34 ***	176 **	6.8 ***
CV*Year	5	0.65 n.s.	16,050 n.s.	110 *	14.18 ***	311 **	4.33 **
CV*Site*Year	3	0.65 n.s.	17,552 n.s.	118 *	0.45 n.s.	119 *	0.38 n.s.
Error(3)†		0.31	7,215	46	0.18	47	0.95

[a]d.f.=degrees of freedom
*=0.01<P<0.05;**=0.01>P>0.001;***=P<0.001; n.s.= not significant
Stand=number of plants per hectare, Seed Survival= % of seed survived, establishment=visual
† Error (1) = replicates within years; Error (2) = site x replicates within years; Error (3) = Pooled replicate error.

Table 2.3 Means squares from the analysis of variance of seed yield, seed oil content, oil yield, number of pods raceme^{-1}, and seeds pod^{-1}, from six cultivars planted at two locations over three years and four replicates.

Source	[a]d.f.	Seed Yield		Seed Oil Content		Oil Yield		Pods Raceme^{-1}		Seeds Pod^{-1}	
Year	2	40,336,330	***	19,491	***	133,591	***	512.0	**	256.2	***
Error (1)†	9	1,163,683	*	493	n.s.	3,691	**	66.1	n.s.	6.0	n.s.
Site	1	16,858,269	***	6,322	**	57,569	***	425.0	**	656.1	***
Site*Year	1	29,514	n.s.	12,545	***	735	n.s.	637.6	**	58.2	*
Error(2)†	4	673,146	n.s.	610	n.s.	2,185	n.s.	75.2	n.s.	10.0	n.s.
CV	5	12,931,017	***	13,617	***	44,008	***	1,367.3	***	168.2	***
CV*Site	9	2,141,771	***	667	n.s.	7,448	***	120.1	*	20.1	n.s.
CV*Year	4	440,957	n.s.	559	n.s.	1,622	n.s.	114.9	n.s.	19.1	n.s.
CV*Site*Year	4	1,218,799	n.s.	924	n.s.	4,310	n.s.	67.4	n.s.	15.2	n.s.
Error(3)†		331,473		443		1,066		48.3		12.4	

[a]d.f.=degrees of freedom

*=0.01<P<0.05;**=0.01>P>0.001;***=P<0.001; n.s.= not significant

† Error(1) = replicates within years; Error(2) = site x replicates within years; Error (3) = Pooled replicate error.

Table 2.4 Crop establishment, seedling stand, winter kill, days from January 1st to 50% flower bloom, plant height, of six cultivars planted at two sites over three years, and four replicates.

Species	CV	Crop Establishment		Seedling Standx10^{-6}		Seedling Survival		Winter kill		Plant height		50% Flower Bloom	
		---1-9†---		-plants ha^{-1}-		---% ---		---1-9‡---		---cm---		-days from Jan 1st-	
B. napus	Amanda	8.4	ab	402,092	ab	34	ab	7.2	a	134	b	132	a
	Durola	8.6	a	338,076	c	28	c	7.1	ab	136	b	131	b
	Dwarf Essex	8.4	ab	447,308	a	37	a	6.8	ab	140	a	130	c
	Wichita	8.3	ab	345,419	bc	29	bc	6.5	c	144	a	131	b
B. rapa	Largo	8.1	b	398,075	ab	33	ab	6.1	d	142	a	127	d
C. sativa	Joelle	7	c	148,516	d	4	d	5.6	e	98	c	125	e
	Mean	8.1		346,581		27		7		132		129	
	s.e.	0.134		20,021		1.598		0.105		1.646		0.239	

† 9 = well emerged, 1 = poorly emerged
‡9=no winter kill,1=all winter kill
Cultivar means within columns with different superscript letters are significantly different (P>0.05), according to Duncan's multiple range test.

Table 2.5 Average seed yield, seed oil content, oil yield, number of pods raceme^{-1}, seeds pod^{-1}, with six cultivars from three species planted at two sites over three years, and four replicates.

Species	CV	Yield	Oil Content	Oil Yield	Seeds per Pod	Number of Pods
		---kg ha^{-1}---	---g kg^{-1}---	--l ha^{-1}--	---seed pods^{-1}†---	-pods raceme^{-1}‡-
B. napus	Amanda	3,252 [b]	418.0 [b]	1,627 [a]	20 [ab]	50 [b]
	Durola	2,965 [bc]	445.7 [a]	1,599 [a]	18 [b]	39 [c]
	Dwarf Essex	2,598 [c]	428.2 [b]	1,361 [b]	18 [b]	42 [c]
	Wichita	3,658 [a]	413.1 [b]	1,805 [a]	21 [a]	37 [c]
B. rapa	Largo	1,950 [c]	397.7 [c]	934 [c]	18 [b]	51 [b]
C. sativa	Joelle	1,148 [e]	344.3 [d]	493 [d]	11 [c]	67 [a]
	Mean	2,595	407.8	1,306	17	48
	s.e.	141.3	5.165	74.94	0.846	1.67

† =average of 5 pods seeds from 3 main racemes
‡=number of pods average from 3 main raceme
Cultivar means within columns with different superscript letters are significant (P>0.05), according to Duncan's multiple range test.

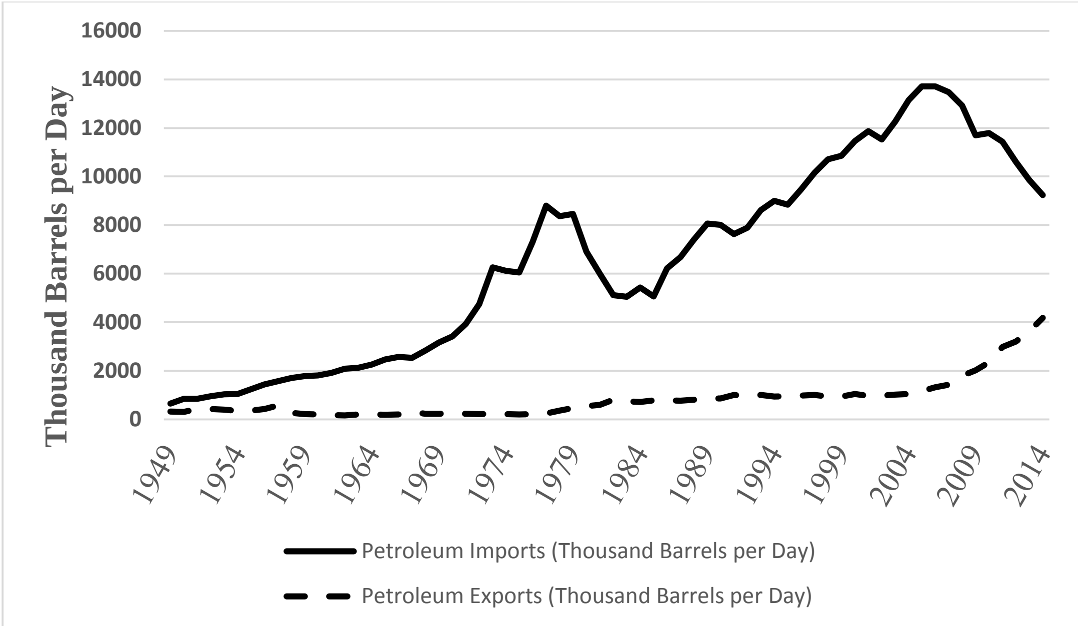

Figure 2.1 Yearly Petroleum Imports *vs.* Exports 1949-2014 (USEIA, 2015e).

Chapter 3: Examining the potential of utilizing spring oilseed Brassicaceae crops (*Brassica carinata* L., *B. juncea* L., *B. napus* L., *B. rapa* L., *Camelina sativa L.*, and *Sinapis alba* L.) as viable oilseed rotation crops with small grain cereals in the dry land agricultural region of the Pacific Northwest.

3.1 Abstract

The Palouse region of the inland Pacific Northwest (PNW) consists of dryland farming covering northern Idaho, eastern Washington and eastern Oregon. Spring planted crops are often grown in rotation with winter wheat which is planted on over 85% of crop land in the region. Although spring crops are grown in the higher rainfall region (mainly barley and legume crops), and attempts have been made to introduce several others, very few spring planted crops have been identified that produce comparable farm returns to winter or spring wheat. In this study the potential adaptability of two *Brassica carinata* (Ethiopian mustard), two *B. juncea* (Indian mustard), four *B. napus* (three spring canola and one spring rapeseed), one *B. rapa* (spring canola), two *Sinapis alba* (yellow mustard) and one *Camelina sativa* (camelina) cultivars were examined in field trials. The experimental design was a randomized complete block with 4 replicates of 12 cultivars from 6 species at each of 2 locations in northern Idaho in 3 years. A range of morphological and physiological plant traits were evaluated throughout the growing season. At harvest seed yield and seed oil content were determined from each plot and used to calculate oil yield. *Brassica napus* cultivars, particularly the high yielding hybrid cultivars (DKL-3042.RR and InVigor.L130-LL) and the *B. juncea* cultivars showed the greatest potential as biofuel feedstock crops in the region. *C. sativa* had intermediate oil yield and could have potential as a biofuel oil feedstock species particularly in the low rainfall regions of the PNW where no alternative spring crops have shown adaptability. *Brassica carinata* cultivars showed little or no

adaptability in the environments of the PNW and have no potential as biofuel feedstock crops. Similarly, *S. alba* cultivars had very low seed oil content and hence may have little potential as biofuel feedstock crops unless the seed meal can be utilized for high value condiment spice or bio-pesticide use.

3.2 Introduction

3.2.1 *PNW agriculture*

Spring planted crops in the dryland regions of northern Idaho are grown in rotation with the predominant crop in the region being winter wheat (*Triticum aestivum* L.) (USDA, NASS, 2015). The Palouse region of the inland Pacific Northwest (PNW) consists of 1.3 million hectares (M ha) of dryland farming stretching over northern Idaho and eastern Washington and into eastern Oregon. In the Palouse region winter wheat is traditionally planted on over 85% of all hectares. The PNW is the leading U.S. producer of soft white wheat winter wheat, and about 90% of all wheat produced in the region is exported (Kok *et al.*, 2009). In the higher rainfall areas spring wheat is included in rotation with winter wheat mainly to facilitate annual weed control through spring tillage or application of broad spectrum herbicides and for management of plant diseases. Other spring crops include: spring barley (Carr *et al, 2014*); chickpea (*Cicer arietinum L.*), pea (*Pisum sativum*), lentil (*Lens culinaris*) (USADPLC, 2015); and spring canola (*Brassica napus*) (Brown *et al.*, 2008).

Winter wheat traditionally provides the greatest economic return compared to alternative crops in this area (Guy & Lauver, 2006). The U.S. national average yield for all wheat in 2015 was 2,959 kg ha^{-1} (44 Bu $acre^{-1}$), while average yield for all wheat in Idaho was almost double the national average at 5,272 kg ha^{-1} (78.4 Bu $acre^{-1}$) (USDA, NASS, 2015). Not surprisingly high yield potential creates a monetary incentive to growers to produce wheat on a large number of hectares. Growers have achieved consistent high yield under a variety of different tillage systems and precipitation zones. However, traditionally tilled intensified cereal production cropping systems cause soil erosion and long-term sustainability problems (Kok *et al.*, 2009; Schillinger *et al.*, 2009). Although a few spring crops species are grown in the higher rainfall regionals, and attempts have been made to introduce several others, very few (if any) spring crops have been identified that produce comparable farm returns to winter or spring wheat.

3.2.2 *Problems with monoculture*

Traditional winter wheat-fallow cropping systems predominate in the low rain fall regions of the PNW and this can cause severe soil erosion (Guy & Lauver, 2006). However, annual cropping systems in the high rainfall areas provides excellent wind erosion control and increased soil organic carbon (Schillinger, 2009), but concerns of water erosion exists, particularly where there are low crop residues, often after legume crops (Guy & Lauver, 2006).

Monoculture small grain cereal production with few broadleaf rotational crops results in increased grassy weeds (Young *et al.*, 1996), soil borne disease and pest problems, (Krupinsky *et al.*, 2004), and reduced soil health, (Kok *et al.*, 2009; Koenig *et al.*, 2013). Weed control in winter wheat poses the greatest problem to growers as winter annual weed control is limited to cultivation and selective herbicides. Continuous cereal crops will result in increased disease incidence and severity. For example, annual cropping of small grains with high straw residues on or near the soil in some years can contribute to environments where pathogens such as *Rhizoctonia* can persist (Pscheidt & Ocamb, 2015).

3.2.3 *Crop alternatives*

Alternative crop options and well developed rotations are important for sustainable agriculture (Krupinsky *et al.,* 2004). Selecting appropriate diversified crop rotation can be superior for growers agronomically and economically (Kok *et al.,* 2009). Growers may choose to take advantage of spring crops because they use different management systems. Taking advantage of the change in the growing cycle can help with weed management. For example, it has been shown that growing spring canola (*B. napus*) cultivars with herbicide tolerance have been useful tools to clean up weedy fields (Painter *et al.,* 2013).

3.2.4 *Broad leaf rotation crop options*

Traditional broadleaf rotation crops in the higher rainfall regions are legumes (pea, garbanzo bean and lentil). Legumes are ideal rotational crops when grown with wheat as they reduce fertilizer costs of cereal production due to fixing nitrogen (USADPLC, 2015). In addition these crops require less water as they have shallow root systems which do not deplete ground water for the following cereal crops. However, legume crops in this region produce low crop residues which in turn leads to soil erosion.

3.2.5 *Brassicaceae crop options*

Brassicaceae species that might have value in rotational crops in the PNW include canola and rapeseed (*B. napus* or *B. rapa*), condiment Indian and yellow mustard (*B. juncea* and *S. alba*, respectively) and more recently considered crops such as Ethiopian mustard (*B. carinata*) and camelina (*C. sativa*).

Brassicaceae crops are valuable rotation crops to break up pest and disease cycles. Some regional growers have noted the benefits of Brassicaceae as rotational crops to, decrease weed and disease pressure and improve soil quality and subsequent wheat yield

(Painter *et al.,* 2012). Including Brassicaceae oilseed crops in rotation with small grain cereals like wheat and barley have shown positive effects on subsequent wheat yields, grain quality, and disease depending on environmental conditions (Kirkegaard *et al.,* 1994; Heenan, 1995; Angus *et al.*, 1999; Norton *et al.*, 1999), and merit greater investigation (Hocking, *et al.,* 1997). In addition Brassicaceae crops produce high plant biomass compared to legume crops that can reduce soil erosion (Guy, 1999) and increase soil organic matter. Deep penetrating tap root systems can break up hard pans in the soil, and allow better water infiltration.

Brassicaceae oilseed crops canola, rapeseed, and mustard are relatively recent introductions in the PNW region. Although recent price increases of canola has resulted in a four-fold increase in canola hectares, mainly of winter canola (CIFA, 2014), canola hectares remains relatively low. Other Brassicaceae crops (i.e. Ethiopian mustard and Camelina) have yet to be fully investigated for their general adaptability in the PNW.

3.2.5.1 *Evolution and history of Brassicaceae oilseed crop species*

A brief overview of the potential seed yield and seed oil content that have been found along with major characteristics of the Brassicaceae oilseed crops examined in this study are presented in Table 3.1.

Brassica napus is grown for either rapeseed or canola quality seed oils. Rapeseed oil refers to the industrial form of oil derived from *Brassica* species. Rapeseed cultivars are cultivars that have high concentrations of erucic acid, a 22 carbon fatty acid with a single double bond in the seed oil. Older rapeseed cultivars (i.e. see ‘Dwarf Essex’ below) can have high glucosinolate content in the seed meal; although all newer cultivars have low glucosinolate content (i.e., comparable to canola with less than 30 µmoles of total glucosinolate per gram of defatted seed meal). Canola oil refers to the edible form of oil, produced by *Brassica napus* or *B. rapa*. This definition is in compliance with the Canadian standard where the oil must contain less than 2% erucic acid and where the residual meal contains less than 30 µmoles of total glucosinolate per gram of defatted meal. In the past few years a mustard species (*B. juncea*) have been modified to produce the same oil profile and meal quality as canola and in the future other cultivars also may be considered as canola species.

Brassica napus oilseed crops (i.e. canola or rapeseed) are naturally produced amphidiploids from *B. rapa* and *B. oleracea* hybridization (McNaughton, 1976). Annual and biennial types are available and breeding efforts in the U.S. and throughout the world have developed adapted cultivars for various regions of oilseed production. The University of Idaho Canola & Rapeseed Breeding Program has been developing adapted spring canola and rapeseed cultivars for over 24 years.

Ethiopian mustard (*B. carinata*) also is an amphidiploid species which evolved from a natural hybridization between *B. nigra* and *B. oleracea* (Scarisbrick *et al.*, 1986). *Brassica carinata* has been identified as a promising oil feedstock for cultivation in coastal Mediterranean climates (Cardone *et al.*, 2002), and recent breeding efforts in Canada have led to new cultivars with the focus being oil feedstock crops for bio-jet fuel production (Agrisoma, 2015).

Brassica juncea (brown or Indian mustard) is a naturally developed amphidiploid from hybridization between *B. nigra* and *B. rapa* (Scarisbrick *et al.*, 1986). *Brassica juncea* is adapted to drier growing conditions and is widely produced in Northern India and China where yellow and brown seeded varieties are available (Booth & Gunstone, 2004). The University of Idaho has developed cultivars of *B. juncea* that are adapted to the PNW.

There is some disagreement on the originator species for *B. rapa*; however, it is native throughout Europe, Russia and central Asia with vast genetic variation and use. It has been thought to have developed in two different centers of origin, one Europe, one Asia (Bañuelos *et al.*, 2013). Research into various factors regarding the performance of *B. rapa* crops have been conducted in the PNW region for some time.

The origin and early evolution of *C. sativa* is believed to be from Eastern Europe (Ghamkhar, 2010; Eynck & Falk, 2013). It has been grown as a crop throughout Russia and Europe, but production waned through the middle ages as other oil crops (mainly rapeseed) had become more common (Eynck & Falk, 2013). Interest in *C. sativa* increased as it was re-introduced as a crop for a second time, in the development of the New World, and was later praised for its tenacity as a low input oil crop (Eynck & Falk, 2013).

Sinapis alba (yellow or white mustard) production has focused on its use as a condiment spice mustard utilized for its ‘pungent’ flavor characteristic. The eastern Mediterranean is believed to be its center of origin. It has also been considered a valuable oilseed crop and was widely grown in Sweden for this purpose from 1940-1950. The major center of genetic improvement has come from England and Canada with the goal of condiment quality. German improvement has led to varieties with enhanced green manure characteristics (Hemingway, 1976).

3.2.6 *Research objective*

This project investigates the agronomic adaptability of twelve Brassicaceae oilseed cultivars crop from six different Brassicaceae species , grown at two different locations over 3 years to determine morphological and physiological characteristics, seed yield, seed oil content and hence determine the potential of each oilseed species as a rotation crop with winter wheat.

Specific objectives of this research are:

- To determine the potential of utilizing Brassicaceae oilseed species and cultivar within species for bio-fuel feedstock crops.
- Determine adaptability and possible profitability and rotational impact of different Brassicaceae oilseed crops and subsequent winter wheat (the latter being presented in Chapter 4).

3.3 Materials and Methods

3.3.1 *Site and trial specifications*

Field trials were planted at the University of Idaho Parker Research Farm in Moscow, ID (46°43'N 116°57'W) with an average precipitation of 69 cm and a Palouse silt loam soil type with a 0-3% slope; and at the University of Idaho Kambitsch Research Farm (46°55'N, 116°92'W) near Genesee, ID, with an average precipitation of 45 cm and a Naff Palouse silt loam complex that is found throughout the northern Idaho region.

The previous crop at each site was spring barley. Prior to planting the ground was chisel plowed in the preceding fall. The herbicide Trifluralin: (α,α,α-Trifluoro-2, 6-dinitro-N,N-dipropyl-p-toluidine) was applied pre-plant at a rate of 2.33 l ha^{-1} and incorporated uniformly to a depth of 10 cm across the trial area. Each trial area was pre-plant fertilized with a 50:50 blend of urea (46-0-0) and ammonium sulfate phosphate (16-20-15) to give an overall rate of (31-10-7.5) {$N:P_2O_5:K_2O^-S$ } at 336 kg ha^{-1} to give approximately 100 kg of N ha^{-1} uniformly across each trial.

Plots size was 3.07 m x 8.00 m in 2013, however, 2014 and 2015 plot dimensions were 3.58 m x 8.00 m; to accommodate the use of spraying equipment. All trials were planted with a single cone, double disc opener plot planter, planting six rows 13 cm apart and each plot was planted as 3 passes of the plot planter. Planting depth was uniform across individual trials and was adjusted at each trial to the appropriate moisture depth (1-3 cm), depending on the individual site year soil moisture level.

Field trials were planted at Moscow during three years and at Genesee during two years. Trials at Moscow were planted on May 2nd in 2013, May 1st in 2014, and April 4th in 2015, while trials at Genesee May 2nd in 2014, and April 27th in 2015.

DKL-3042.RR was treated with Prosper 400™ (clothianidin, thiram, carboxin, metalaxyl) at a rate of 16.3 mL kg^{-1} and InVigor.L.130-LL was treated with Prosper EverGol™ (clothianidin, penflufen, trifloxystrobin, metalaxyl) at a rate of 739 mL of fungicide to 45.36 kg^{-1} of seed. Seed from other cultivars, except *C. sativa*, was treated with Helix Xtra™ (thlamethoxam, difenoconazale, mefenoxam, fludioxonil) prior to planting at a rate of 15 mL kg^{-1} seed, to protect against soil and seed borne fungal pathogens, and to provide early season insecticide, mainly to reduce flea beetle (*Psylliodes cruciferae*) damage. *Camelina sativa* seed was not treated prior to planting as no seed treatments are currently labeled for the crop.

In 2013 and 2014, few weeds were observed and weed control was by hand-weeding. However, in 2015 both sites had severe weed pressure and additional management was needed. Entries that were herbicide tolerant were treated with their respected chemical, the remaining plots were extensively hand weeded. Plots were monitored for insect infestation and when appropriate insecticides were applied. Only cabbage aphids (*Brevicoryne* *brassicae*) and flea beetles (*Psylliodes cruciferae*) were observed and controlled with foliar application of Warrior II (Lambda-cyphalothrin) insecticide (Syngenta, 2014). Observations for disease were not actively recorded; however, continuous weekly scouting of individual plots in trials showed no visual variation, signs or symptoms from potential pathogens.

3.3.2 *Cultivars examined and seeding rates*

The performance of two *B. carinata* (Ethiopian mustard), two *B. juncea* (Indian mustard), four *B. napus* (three spring canola and one spring rapeseed), one *B. rapa* (spring canola), two *S. alba* (yellow mustard) and one *C. sativa* (camelina) cultivars were examined in field trials. Different seeding rates were used for the different species examined and rates were adjusted according to the germination rate of each seed lot.

3.3.2.1 *Brassica carinata*

Two Ethiopian mustard cultivars developed by Agrisoma PLC specifically for the role of a non-food crop biofuel feedstock were examined (‘AAC-A110’ and ‘0808146M’). *Brassica carinata* cultivars AAC-A110 (application number 12-7817) & 0808146M had a target seeding rate of 840,000 seed ha^{-1} (CFIA, 2012).

3.3.2.2 *Brassica juncea*

The spring *B. juncea* cultivar ‘Oasis’ has canola oil and seed meal quality and was developed by Viterra (Potts, 2010). ‘Pacific Gold’ (PI 633009) condiment spice Indian mustard was developed by the University of Idaho (Brown; *et al.*, 2005). Both *B. juncea* cultivars had a target seeding rate of 1,800,000 seed ha^{-1}.

3.3.2.3 *Brassica napus*

Three spring *B. napus* canola cultivars (‘DKL-3042.RR’, ‘Empire’, and ‘InVigor.L130-LL’) and the spring rapeseed *B. napus* cultivar (‘Gem’), were examined. DKL-3042.RR is a hybrid cultivar developed by DeKalb as a spring canola with tolerance to glyphosate (*N*-(phosphonomethyl) glycine) herbicides. It has been shown to have outstanding yield potential and stability in previous PNW yield tests, in addition to early maturity and high oil content. InVigor.L130-LL is a hybrid cultivar developed by Bayer Crop Science as a LibertyLink® glufosinate herbicide tolerant variety with medium height and slightly early flowering and high yielding cultivar for food quality oil. Empire is an open-pollinated cultivar developed by the University of Idaho as an adapted spring canola line for food grade oil. Gem (PVP-201100052) is a spring open-pollinated rapeseed cultivar developed by the University of Idaho and has industrial (high erucic acid) oil quality but low glucosinolate (canola-quality) seed meal. Gem is tolerant to imadazilinone class herbicides. Each *B. napus* cultivar had a target seeding rate of 1,200,000 seed ha^{-1}.

3.3.2.4 *Brassica rapa*

One *B. rapa* cultivar (‘Eclipse’) that was developed at the University of Alberta with low glucosinolate meal content (Degenhardt, *et al.*, 1992) was included. *Brassica rapa* cultivar Eclipse had a target seeding rate of 1,200,000 seed ha^{-1}.

3.3.2.5 *Camelina sativa*

The *C. sativa* cultivar ‘CO.466’ was developed in at Montana State University and had a target seeding rate of 3,840,000 seed ha^{-1}. Camelina seed being substantially smaller compared to other entries required this substantial difference in seeding rate to achieve an appropriate plant density applicable to commercial production.

3.3.2.6 *Sinapis alba*

Two *S. alba* condiment spice mustard cultivars (IdaGold and Tilney) were examined. IdaGold (PI 597356) yellow mustard was developed by the University of Idaho (Brown, *et* *al.*, 1996). Tilney mustard was released by Colman Foods Norwich, England, and is distributed in the U.S. and Canada by Minn-Dak Growers Association, Grand Forks, ND. Each *S. alba* cultivar was planted at a target seeding rate of 1,200,000 seed ha^{-1}.

3.3.3 *Experimental design*

The experimental design was a randomized complete block with 4 replicates of 12 cultivars from 6 species at 2 locations in each of 3 years. Note that in the first year, only the Moscow site was planted.

3.3.4 *Data collected*

Crop establishment was measured visually after seedling emergence and scored from 1 to 9 with 9 representing 100% uniform seedling emergence. Plant stand was measured once plants had reached the 5 to 6 leaf stage, by counting the number of plants per linear meter. Counts were taken from the center of the plot to avoid edge effects. To evaluate seed survival we divided the stand ha^{-1} from the target stand rate. Indirect leaf area index (LAI) was recorded throughout the growing period for each plot using an AccuPAR LP-80 (Decagon, 2003). Days from planting to 50% flower bloom was recorded from all trials.

Plant height was recorded after bloom end from plants growing in the middle of each plot. Pod characteristics were recorded by cutting 3 main racemes from each plot and counting pods on each raceme. Thereafter 3 representative pods were opened from each raceme to determine the number of seed pod^{-1}. Lodging was evaluated visually on a 1 to 9 scale with 9 meaning no lodging present.

At crop maturity, plots were directly harvested using a Wintersteiger Classic™ (Wintersteiger, Inc.; Salt Lake City, UT) small plot combine. Recommended settings for oil seeds Brassicaceae crops were used. However, settings with *C. sativa* plots were adjusted to account for smaller seed size and difficulties encountered in separating seed from chaff. Harvested seed was air- dried at 50° C for 2 days and was weighed to determine each individual plots yield.

Camelina sativa harvested samples contained high chaff levels and were hand cleaned by sieves before its weight was determined.

Sub-samples of seed were taken from each plot to determine seed oil content. Oil content was determined on single 12-g samples following the procedures outlined by Hammond (1991) using a Newport MKIIIA Nuclear Magnetic Resonance (NMR) Analyzer (Oxford Instruments Inc., Concord, MA). The NMR was calibrated with a single reference sample of known oil content of the appropriate species and the sample analysis carried out as described by Howard and Daun (1991). Oil yield was determined by calculating l ha^{-1} (gal a^{-1}) equivalent from seed yield and seed oil content.

3.3.5 *Data analysis*

Data was analyzed using a general linear model, and Duncan's multiple range tests (SAS, 2009). All computations were carried out using the Statistical Analysis Software (SAS, 2009) program for the entire data set. Leaf Area Index data was averages and graphed using Microsoft Excel (2013).

3.4 Results

Means squares from the analyses of variance of seedling stand, seedling survival, crop establishment, plant height, lodging, and 50% bloom date are presented in Table 3.2. Means squares from the analyses of variance of yield, oil content, oil yield, pods $raceme^{-1}$, and seeds pod^{-1} are presented in Table 3.3.

Significant year differences were observed for all pre- and post-harvest characters recorded. Similarly, site differences were significant for most traits except oil content, and lodging was only observed at one site in 2013. The site x year interaction was significant for seedling stand, crop establishment, days to 50% bloom, seed yield, oil yield, and seeds pod^{-1}. The cultivar x site interaction was highly significant for all variables except number of pods raceme^{-1}. The cultivar x year interaction was significant for seedling stand, crop establishment, days to 50% bloom, seed yield, seed oil content, oil yield, seeds pod^{-1}. The three-way interaction cultivar x site x year, was significant for seedling establishment, days to 50% bloom, seed yield, seed oil content, oil yield, number of pods raceme^{-1}, seeds pod^{-1}. It should be noted that most cultivar interaction effects were small in comparison to the main effects of cultivars and in most of the cases the cultivar interactions were scalar and did not have major changes in cultivar rankings.

3.4.1 *Species and cultivar effects - Pre harvest traits*

Brassica carinata cultivars tended to have a poor stand counts, additionally these lines had the worst crop establishment ratings (Table 3.4). *Brassica carinata* cultivars had very large seed size and a high proportion of planted seeds did not emerge. However, the few seedlings that did survive developed aggressively. *Brassica carinata* plants were taller than other species but had stiff straw and showed few problems with lodging. *Brassica carinata* lines had the latest flower start from planting that may have left them susceptible to excessive heat stress.

Brassica juncea tended to have a high stand count; however, both *B. juncea* cultivars had very poor seed survival compared to their target seeding rate. *Brassica juncea* lines had higher average plant height scores, Pacific Gold specifically had the highest plant height average. The taller plants may attribute to lodging issues. Days from planting to 50% bloom in *B. juncea* cultivars tended to be earlier than the other species examined and is expected for this species.

Brassica napus cultivars all had similar stand counts and crop establishment, but varying seed survival. Plant height of *B. napus* cultivars was relatively uniform except for InVigor.L130-LL (135 cm) the tallest of all entries. All *B. napus* entries experienced some lodging, except the stiff straw cultivar InVigor.L130-LL. Days to 50% flowering in *B. napus* cultivars was around 48 d, however, InVigor.L130-LL flowered significantly later than the other three *B. napus* cultivars.

Brassica rapa had a reasonable stand. Crop establishment, plant height and lodging for *B. rapa* tended to moderate compared to the species examined, however, *B. rapa* was very early flowering.

CO.466 (*C. sativa*) had markedly different plant morphology than all other entries in the trial. While CO.466 had substantially higher stand count than all other species, seed survival was significantly lower. This may be due to *C. sativa's* smaller seeds having a harder time successfully emerging through the soils at the two locations tested. CO.466 was significantly shorter (88 cm) in stature than all other cultivars and showed no lodging. *Camelina sativa* appeared to flower late, but it should be noted that determining exact bloom dates proved more difficult as its flower structure and morphology was vastly different from the other species examined.

Sinapis alba cultivars had good plant stand. However, IdaGold, stand was significantly better than Tilney. IdaGold also showed higher average seedling survival, crop establishment, and taller plant height compared to Tilney. Both *S. alba* cultivars flowered very early compared to the other species. .

3.4.2 *Leaf area index*

Recordings of indirect leaf area index (LAI) was determined using an AccuPAR LP-80 at weekly intervals pre-bolting to flower ending. LAI for the four *B. napus* cultivars (Figure 3.1), two *B. juncea* and two *S. alba* cultivars (Figure 3.2), and the remaining two *B. carinata* cultivars, *B. rapa* and *C. sativa* cultivar (Figure 3.3) were combined over years and sites and plotted against time. Quadratic relationships for each cultivar was determined and from this the maximum LAI, days from planting to maximum LAI was calculated and days after planting (DAP) to achieve maximum LAI is determined (Table 3.5).

Highest LAI was from the *S. alba* cultivars IdaGold (LAI=3.57) and Tilney (LAI=3.43). In general LAI of *B. napus* cultivars was high; 3.47, 3.33, and 3.27 for DKL-3042.RR, InVigor.L130-LL, and Empire, respectively, although the *B. napus* cultivar Gem had the lowest LAI of all 12 cultivars examined. The lowest LAI was found in *B. juncea*, cultivar Oasis (LAI=2.44), *B. rapa* Eclipse (LAI=2.62), and *C. sativa* CO.466 (LAI=2.68). LAI of *B. carinata* cultivars was intermediate.

The late flowering *B. carinata* cultivars took most DAP to achieve maximum LAI, 68.2 and 68.0 DAP for AAC.A110 and 0808146M, respectively. Not surprisingly, the very early flowering *S. alba* cultivars achieved maximum LAI 60.4 DAP (IdaGold) and 65.5 DAP (Tilney) after planting. It is known from past trials that IdaGold tend to establish quickly and reach full canopy early, out competing weeds (Brown, *pers comm*). *Brassica napus* cultivars reached maximum LAI at very similar times between 64.9 DAP for DKL-3042.RR and 63.1 DAP for the later flowering cultivar InVigor.L130-LL. The *B. juncea* cultivar Pacific Gold reached maximum LAI 62.1 DAP, while the later Oasis reached LAI maximum 3.7 days later.

LAI is often used in plant models to predict yield potential. Multiple regression of LAI onto yield showed no significant relationship between species. There was a suggestion within species that higher maximum LAI was associated with higher seed yield, but this was not consistent.

3.4.3 *Yield, oil content, oil yield and yield components*

The highest seed yield was obtained from the hybrid *B. napus* cultivars DKL-3042.RR (1,676 kg ha^{-1}), InVigor.L130-LL (1,460 kg ha^{-1}), Pacific Gold (1,450 kg ha^{-1}), and CO.466 (1,435 kg ha^{-1}), while lowest seed yield was from the two *B. carinata* cultivars AAC-A110 (1,019 kg ha^{-1}) and 0808146M (1,211 kg ha^{-1}), the two *S. alba* cultivars IdaGold (1,031 kg ha^{-1}) and Tilney (1,070 kg ha^{-1}), and *B. rapa* cultivar Eclipse (1,043 kg ha^{-1}) (Table 3.6). Low yielding *S. alba* had many pods $raceme^{-1}$ but with averaged seeds pod^{-1}. Similarly the low yielding *B. carinata* cultivars had few pods $raceme^{-1}$ and also low seeds pod^{-1}. Higher yielding *B. napus* cultivars tended to have more seeds pod^{-1} rather than more, pods $raceme^{-1}$ and hence greater advances in selecting for higher yield may be directed towards increasing seed numbers.

Highest seed oil content (406 g kg^{-1}) was produced from the spring rapeseed cultivar Gem, most likely related to the longer esters (erucic acid, 22:1) compared to those which predominate in canola (oleic acid, 18:1). Lowest oil content was found in the *S. alba* condiment spice mustard species (253 g kg^{-1} and 256 g kg^{-1} for IdaGold and Tilney, respectively). As low oil content is desirable in yellow mustard cultivars it is highly likely that these were specifically selected to have low seed oil. *Brassica carinata* and *C. sativa* cultivars also had markedly lower oil content compared to *B. napus* or *B. rapa*, both more traditional oilseed types. *Brassica juncea* cultivars showed intermediate oil content with the canola-quality Oasis having higher oil content than the condiment spice cultivar Pacific Gold.

Combining seed yield and oil content, the greatest biofuel feedstock potential would be from *B. napus*, particularly the hybrid *B. napus* cultivar DKL-3042.RR which produced 795 l ha^{-1} (88 gal $acre^{-1}$), and the *B. juncea* cultivars Oasis 636 l ha^{-1} (~70 gal $acre^{-1}$) and Pacific Gold 617 l ha^{-1} (~68 gal $acre^{-1}$). The *B. juncea* cultivars are relatively more stress tolerant (heat and drought) and may have greater potential in stress situations which can adversely impact *B. napus* cultivars. The least potential as biofuel feedstock crops would be the low oil content *S. alba* cultivars with only 318 l ha^{-1} (35 gal $acre^{-1}$) and 327 l ha^{-1} (36 gal $acre^{-1}$), or the *B. carinata* cultivars which each produced 456 l ha^{-1} (50 gal $acre^{-1}$). *C. sativa* cultivar CO.466 did relatively well producing 570 l ha^{-1} (63 gal $acre^{-1}$) which although markedly lower than *B. napus* or *B. juncea* may have potential in the hotter and drier regions of the PNW.

3.5 Conclusions and Recommendations

Similar to the findings of Chapter 2, *B. napus* cultivars, particularly the high yielding hybrid cultivars (DKL-3042.RR and InVigor.L130-LL) and *B. juncea* cultivars (Pacific Gold and Oasis) have the greatest potential as biofuel feedstock production. The *B. juncea* cultivars are more stress tolerant (heat and drought) and may have greater potential in the intermediate rainfall regions of the PNW (28 to 34 cm precipitation) where traditional spring canola and rapeseed can experience yield loss due to high temperature and drought stress at flowering and grain fill.

Camelina sativa had intermediate oil yield and could have potential as a biofuel oil feedstock species particularly in the low rainfall regions of the PNW where no other spring crops have shown any adaptability. Although it was thought that camelina could offer an opportunity to eliminate one fall year out of two (i.e. rather than wheat-fallow-wheat-fallow use wheat-camelina-wheat-fallow), preliminary studies (Brown, *pers comm*) show severe yield reductions in winter wheat following camelina compared to winter wheat following fallow.

Brassica carinata cultivars showed little or no adaptability in the PNW and have no potential as biofuel feedstock crops. Similarly, *S. alba* cultivars have little potential as biofuel feedstock crops unless the seed meal can be utilized for high value purposes, for example as a bio-pesticide (Handiseni *et al.*, 2013).

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Table 3.1. Suggested yield potential, potential seed oil content, and species notes of six Brassicaceae oilseed species examine in the study.

Species	Possible Yield	Oil Content	Notes
	- kg ha^{-1} -	-- % --	
B. carinata†	n.a.	30-35	Ethiopian mustard that is relatively new to the oil market and has had some success in Canada, but little examination in the PNW.
B. juncea‡	2000-2240	35-40	Grown for spice, additionally used as an oil crop in India, this species has cultivars that are adapted for production regionally.
B. napus‡‡	2000-2470	40-45	The most predominant oilseed brassica in production for: Canada, China, EU, and United States.
B. rapa‡‡	1120-1680	38-41	Early maturing, shatter resistant traits with higher oil, however lower yield than other oilseed cultivars.
C. sativa†	560-1680	30-35	This species is rapidly gaining interest as a nonfood oil feedstock crop and has been used in the production of jet fuel.
S. alba‡	560-1680	30-35	Largely grown for condiment spice, it's part of the Brassicaceae family and may offer stress tolerance depending on environment.

† Brown (*pers. comm.*); ‡ Davis *et al*., 2008; Davis *et al*., 2010; ‡‡ Davis *et al*., 2012; Davis *et al*., 2013; Pakish *et al*., 2015.

Table 3.2 Means squares from the analysis of variance of seedling stand, seed survival, crop establishment, plant height, and lodging, and days from planting to 50% flower bloom, from 12 cultivars planted at two locations over three years and four replicates.

Source	[a]d.f.	Stand x 10^{-6}	Seed Survival	Establishment	Plant Height	Lodging	50% flower bloom
Year	2	61,572 *	533 **	21.057 ***	2316 ***	38.268 ***	500.893 ***
Error (1)†	9	13,089 n.s.	45 n.s.	1.134 *	296 ***	0.532 ***	6.998 n.s.
Site	1	558,117 ***	2,326 ***	61.160 ***	2930 ***	0.000 n.s.	205.394 ***
Site*Year	1	58,686 *	145 n.s.	5.526 **	197 n.s.	0.000 n.s.	24.803 **
Error (2)†	6	4,630 n.s.	24 n.s.	0.291 n.s.	109 n.s.	0.000 n.s.	0.591 n.s.
CV	11	170,094 ***	817 ***	3.011 ***	2643 ***	4.082 ***	332.381 ***
CV*Site	22	28,497 **	174 **	1.400 ***	246 ***	3.956 ***	11.589 ***
CV*Year	11	66,443 ***	143 n.s.	1.442 **	224 ***	0.000 n.s.	4.627 n.s.
CV*Site*Year	11	20,230 n.s.	92 n.s.	1.009 *	120 n.s.	0.000 n.s.	8.180 *
Error (3)†	151	1,484	82	0.497	67	0.092	3.638

[a]d.f.=degrees of freedom

*=0.01<P<0.05;**=0.05<P<0.001;***=P<0.001; n.s.= not significant

† Error (1) = replicates within years; Error (2) = site x replicates within years; Error (3) = Pooled replicate error

Table 3.3. Means squares from the analysis of variance of seed yield, seed oil content, oil yield, number of pods raceme^{-1}, and seeds pod^{-1}, from six cultivars planted at two locations over three years and four replicates.

Source	[a]d.f.	Seed Yield	Seed Oil Content	Oil Yield	Pods raceme^{-1}	Seeds Pod^{-1}
Year	2	7,792,151 ***	11,087 ***	16,157 ***	412.2 ***	1,695.6 ***
Error (1)†	9	56,540 n.s.	541 **	189 n.s.	35.9 n.s.	4.1 n.s.
Site	1	17,300,256 ***	773 n.s.	37,817 ***	470.1 ***	2,722.6 ***
Site*Year	1	2,066,368 ***	531 n.s.	3,240 ***	84.5 n.s.	2,398.5 ***
Error (2)†	6	183,007 **	257 n.s.	327 *	74.0 n.s.	6.9 n.s.
CV	11	955,659 ***	46,581 ***	4,820 ***	3,284.6 ***	554.7 ***
CV*Site	22	311,935 ***	589 ***	731 ***	44.7 n.s.	33.4 ***
CV*Year	11	181,376 ***	522 **	622 ***	45.0 n.s.	38.0 ***
CV*Site*Year	11	136,855 **	563 **	398 **	95.1 **	50.2 ***
Error (3)†	151	53,027	215	132	34.6	6.4

[a]d.f.=degrees of freedom

*=0.01<P<0.05;**=0.05<P<0.001;***=P<0.001; n.s.= not significant

† Error (1) = replicates within years; Error (2) = site x replicates within years; Error (3) = Pooled replicate error.

Table 3.4. Seedling stand, seedling survival, crop establishment, plant height, lodging and days from planting to 50% flower bloom of twelve cultivars planted at two sites over three years, and four replicates.

Species	CV	Stand	Seed Survival	Crop Establishment	Plant height	Lodging	50% flower bloom
		-- plant ha^{-1} --	---- % ----	---1-9†---	--- cm ---	---1-9‡---	-days from planting-
B. carinata	0808146M	318,029 ^{d}	37.9 ^{ab}	7.2 ^{c}	127 ^{bc}	9.0 ^{a}	53 ^{a}
	AAC-A110	343,601 ^{cd}	40.9 ^{a}	7.2 ^{c}	123 ^{c}	9.0 ^{a}	52 ^{a}
B. juncea	Oasis	444,418 ^{b}	24.7 ^{ef}	7.9 ^{b}	123 ^{c}	8.4 ^{c}	43 ^{c}
	Pacific Gold	354,182 ^{cd}	19.7 ^{f}	8.1 ^{ba}	133 ^{a}	8.8 ^{a}	43 ^{c}
B. napus	DKL-3042.RR	346,556 ^{cd}	28.9 ^{cde}	8.2 ^{ba}	113 ^{d}	8.2 ^{c}	49 ^{b}
	Empire	348,418 ^{cd}	29.0 ^{cde}	8.1 ^{ba}	118 ^{d}	8.3 ^{c}	48 ^{b}
	Gem	387,396 ^{bcd}	32.3 ^{bcd}	8.3 ^{ba}	113 ^{d}	8.4 ^{c}	48 ^{b}
	InVigor.L130	339,780 ^{cd}	28.3 ^{cde}	8.1 ^{ba}	135 ^{a}	9.0 ^{a}	52 ^{a}
B. rapa	Eclipse	330,080 ^{cd}	27.5 ^{ed}	7.8 ^{b}	114 ^{d}	8.6 ^{b}	41 ^{d}
C. sativa	CO.466	724,530 ^{a}	18.9 ^{f}	8.1 ^{ba}	88 ^{e}	9.0 ^{a}	48 ^{b}
S. alba	IdaGold	411,204 ^{bcd}	34.3 ^{bcd}	8.5 ^{a}	130 ^{ab}	8.8 ^{a}	40 ^{d}
	Tilney	310,387 ^{d}	25.9 ^{ed}	7.9 ^{b}	116 ^{d}	9.0 ^{a}	41 ^{d}
	Mean	388,215	29.0	7.9	119	8.7	47
	s.e.	29,542	2.197	0.171	1.991	0.074	0.463

† 9 = well emerged, 1 = poorly emerged

‡9 = no lodge, 1=all lodge

Cultivar means within columns with different superscript letters are significantly different (P>0.05), according to Duncan's multiple range test.

Table 3.5. Maximum Leaf Area Index (LAI), relative ranking, days after planting (DAP) when maximum LAI is reached, and relative ranking of 12 cultivars from six Brassicaceae oilseed crop species.

Species	Cultivar	LAI-Max	Rank	DAP to Max-LAI	Rank
B. carinata	0808146M	3.15	7	68.0	2
	AAC.A110	3.27	6	68.2	1
B. juncea	Oasis	2.44	12	65.8	4
	Pacific Gold	3.09	9	62.1	11
B. napus	DKL-3042.RR	3.47	2	64.9	7
	Empire	3.11	8	63.5	9
	Gem	3.27	5	64.8	8
	InVigor.L130-LL	3.33	4	63.1	10
B. rapa	Eclipse	2.62	11	67.5	3
C. sativa	CO466	2.68	10	65.3	6
S. alba	IdaGold	3.57	1	60.4	12
	Tilney	3.43	3	65.5	5

Table 3.6. Means of seed yield, seed oil content, oil yield, number of pods raceme^{-1}, seeds pod^{-1}, of twelve cultivars from six species planted at two sites over three years, and four replicates.

Species	CV	Seed Yield	Seed Oil Content	Oil Yield	Seeds Pod^{-1}	Pods raceme^{-1}
		---kg ha^{-1}---	---g kg^{-1}---	---L ha^{-1}---	--- pods^{-1}†---	---raceme^{-1}‡---
B. carinata	0808146M	1,211 ^{cd}	319 ^{g}	458 ^{d}	14 ^{c}	10 ^{f}
	AAC-A110	1,019 ^{f}	340 ^{f}	420 ^{d}	12 ^{c}	12 ^{f}
B. juncea	Oasis	1,370 ^{b}	389 ^{bc}	636 ^{bc}	13 ^{cd}	37 ^{def}
	Pacific Gold	1,450 ^{b}	358 ^{e}	617 ^{bc}	15 ^{c}	36 ^{de}
B. napus	DKL-3042.RR	1,676 ^{a}	394 ^{b}	795 ^{a}	20 ^{a}	37 ^{cde}
	Empire	1,337 ^{bc}	371 ^{d}	598 ^{c}	20 ^{a}	33 ^{e}
	Gem	1,188 ^{cde}	406 ^{a}	579 ^{c}	20 ^{a}	35 ^{de}
	InVigor.L130	1,460 ^{b}	391 ^{b}	682 ^{b}	21 ^{a}	44 ^{b}
B. rapa	Eclipse	1,043 ^{ef}	380 ^{cd}	477 ^{d}	16 ^{b}	39 ^{cd}
C. sativa	CO.466	1,435 ^{b}	332 ^{f}	570 ^{c}	14 ^{c}	41 ^{bc}
S. alba	IdaGold	1,031 ^{ef}	253 ^{h}	318 ^{e}	5 ^{e}	54 ^{a}
	Tilney	1,070 ^{def}	256 ^{h}	327 ^{e}	5 ^{e}	54 ^{a}
	Mean	1,274	349	542	15	36
	s.e.	55.8	3.6	26	0.6	1.4

† = average of 5 pods seeds from 3 main racemes.

‡ = average number of pods from 3 main raceme.

Cultivar means within columns with different superscript letters are significantly different (P>0.05), according to Duncan's multiple range test.

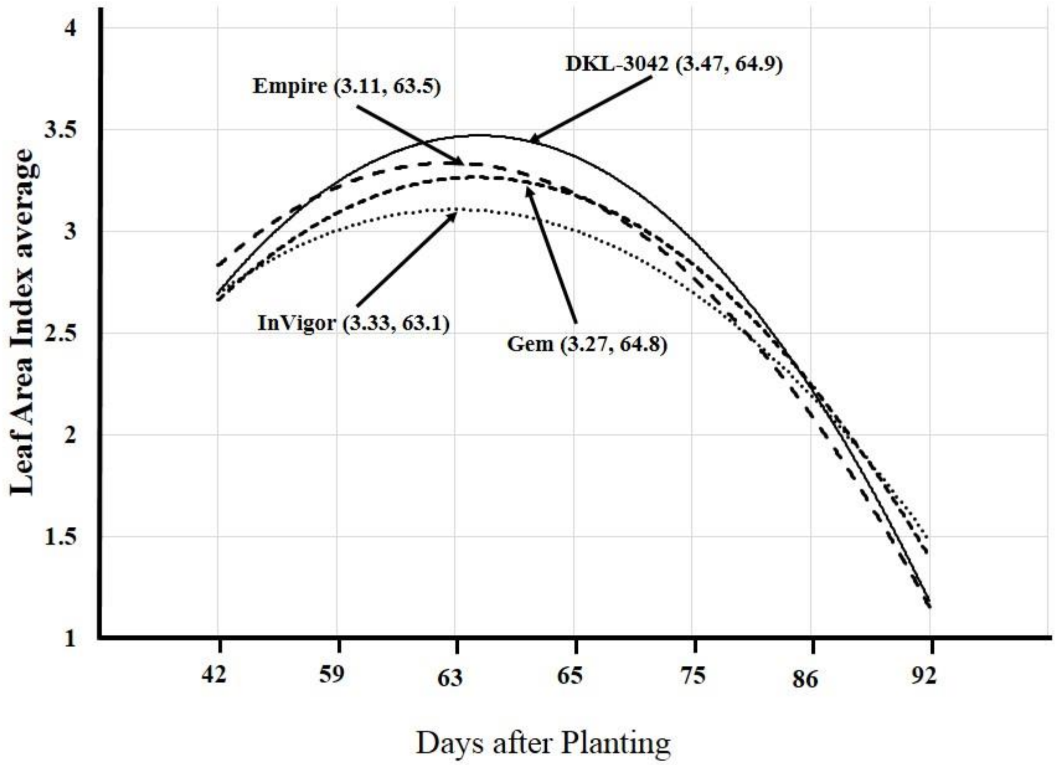

Figure 3.3. Leaf area index (LAI) of four *B. napus* cultivars over time from planting. Shown on the curve is the maximum LAI and days from planting until the maximum LAI is achieved. Maximum LAI and DAP to achieve maximum LAI are shown in parenthesis.

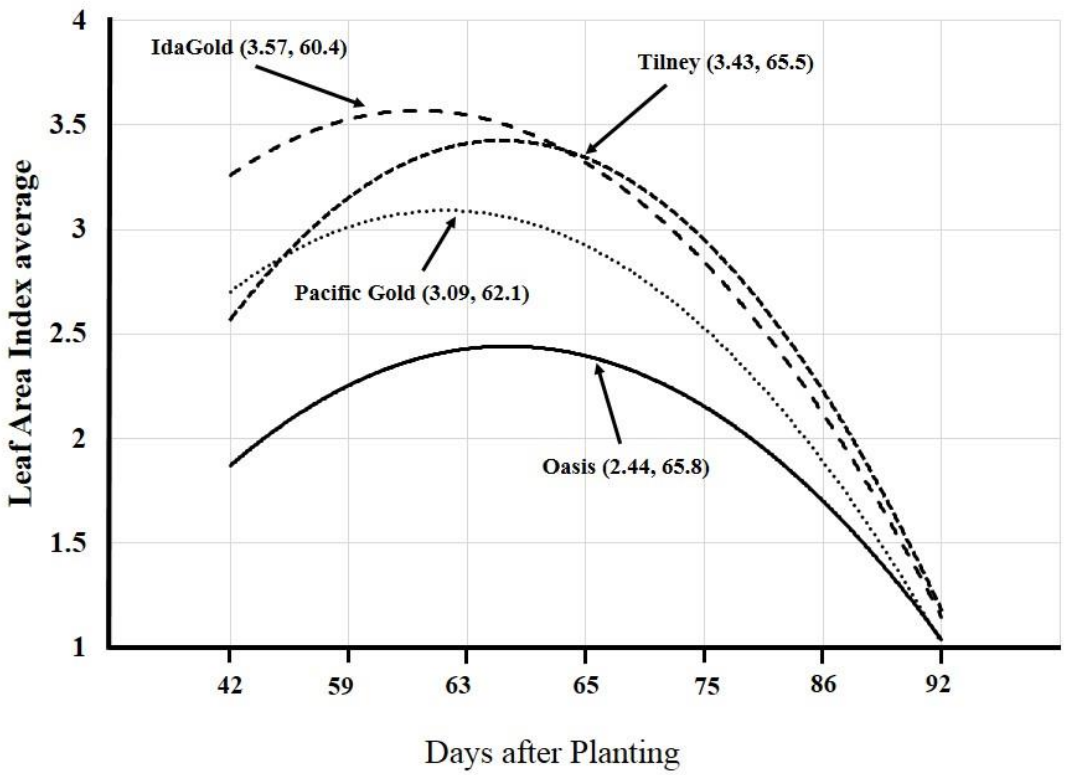

Figure 3.4. Leaf area index (LAI) of two *B. juncea* and two *S. alba* cultivars over time from planting. Shown on the curve is the maximum LAI and days from planting until the maximum LAI is achieved. Maximum LAI and DAP to achieve maximum LAI are shown in parentheses.

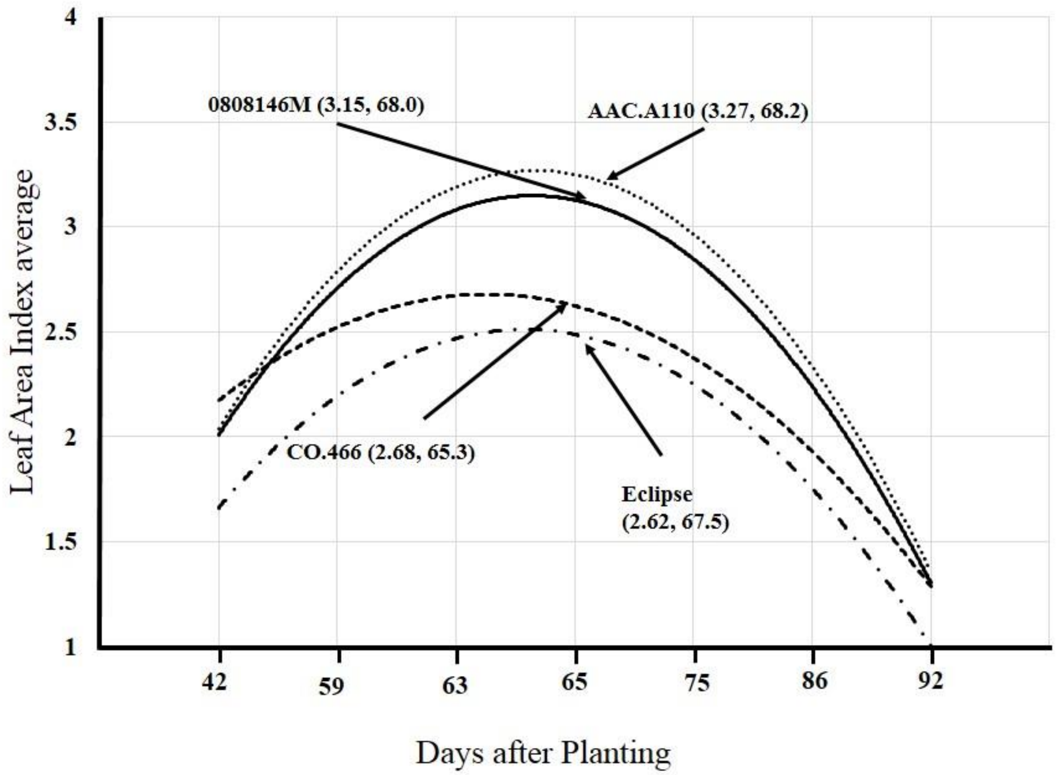

Figure 3.3. Leaf area index (LAI) of two *B. carinata* cultivars, one *B. rapa* cultivar, and one *C. sativa* cultivar over time from planting. Shown on the curve is the maximum LAI and days from planting until the maximum LAI is achieved. Maximum LAI and DAP to achieve maximum LAI are shown in parentheses.

Chapter 4: Winter Wheat (*Triticum aestivum* L.) performance following spring oilseed Brassicaceae crops (*Brassica carinata* L., *B. juncea* L., *B. napus* L., *B. rapa* L., *Camelina sativa L.*, and *Sinapis alba* L.) and winter Brassicaceae crops (*B. napus, B. rapa,* and *C. sativa*) in the dry land agricultural region of the Pacific Northwest.

4.1 Abstract

Wheat has considerable economic value to PNW growers where it is grown on over 85% of the total dryland crop area. However, monoculture small grain cereal production has severe environmental and economic problems and alternative rotational crops are needed to sustain productivity. In this research we examine the relative rotational benefit of winter and spring oilseed crops by combining the productivity of both the oilseed crop and the productivity of the following winter wheat crop. No significant differences were found between grain yield or quality of winter wheat following fall planted *B.* napus, *B. rapa* or *C. sativa*, or indeed following spring planted *B. napus, B. juncea, B. carinata, B. rapa, S. alba* or *C. sativa.* Fields chosen for these field trials had been managed by the University of Idaho and have had a diverse crop rotation, in comparison to the more traditional cereal production where fewer rotation crops are grown. In situations where there had been less diverse crop rotation, the impact of the different oilseed crops on subsequent winter wheat may have been greater that that observed in this study and perhaps subsequent wheat crop would see a greater impact from the introduction of Brassicaceae crops. However, the significant differences in economic return over two cropping years in this study were related only to the different yield return and crop prices of the oilseed crops, with highest grower returns

obtained from the high yielding *B. napus* and *B. juncea* crops and higher value mustard seed.

4.2 Introduction

4.2.1 *Current wheat*

In the U.S., wheat is the third highest hectares crop in the country, behind corn (*Zea mays*) and soybean (*Glycine max*) (Vocke, 2015). In 2015, U.S. winter wheat was planted on 16,430,237 hectare (ha), while 541,064 ha (spring and winter wheat combined) was planted in the state if Idaho (USDA, NASS, 2015). Wheat production in the Pacific Northwest (PNW) began in the late 1800's, and since then technological development of equipment for more efficient farming and better management has helped wheat maintain its place as the primary crop for growers in the dryland region of the PNW (Schillinger & Papendick, 2008). Wheat is of considerable economic value to many regional growers providing better cash returns over any alternative adapted crops.

In 2014, winter wheat in Idaho was planted on 315,655 ha of crop land with an average yield of 5,380 kg ha^{-1} (82 bu a^{-1}), and an estimated value of $375,477,304 ($0.2211 kg^{-1}, equivalent to $6.03 bu^{-1}). Similarly, spring wheat in the same year was planted on 194,249 ha in (predominantly in Southern) Idaho and an average yield of 5,111 kg ha^{-1} (78 bu a^{-1}) with an estimated farm value of $236,287,980 ($0.2380 kg^{-1}, equivalent to $6.49 bu^{-1}) (USDA-NASS, 2014).

4.2.2 *Continuous production is not sustainable*

Cropping systems with a predominance of small grain cereals (i.e. wheat and barley) result in increased grassy weeds (Young *et al.*, 1996), soil borne disease and pests, (Krupinsky *et al.*, 2004; Pscheidt & Ocamb, 2015). In addition, traditional wheat-fallow and annual cropping systems with low crop residues can result in higher soil erosion (Guy & Lauver, 2006), and reduced soil health, (Kok *et al.*, 2009; Koenig *et al.*, 2013).

4.2.3 *Wheat Brassicaceae Rotating*

Including Brassicaceae crops in rotation with wheat has shown positive effects on following wheat yields and quality, and reduced disease (Kirkegaard *et al.*, 1994; Heenan, 1995; Norton *et al.*, 1999; Angus *et al.*, 1999), brassicas deserve greater investigation (Hocking *et al.*, 1997). In addition, Brassicaceae crops produce high, above ground biomass (in excess of 6,000 kg ha^{-1}) and root biomass that reduces soil erosion (Guy, 1999) and can increase soil organic matter. Deep penetrating tap root systems can break up hard pans in the soil, and allow better water infiltration. Including rotational crops has been proven to increase yield of subsequent wheat crops (Hocking *et al*, 1997).

4.2.4 *Research objectives*

The objective of this research was to determine the relative rotation effect of spring and fall planted Brassicaceae oilseed crop species on the performance of winter wheat.

Specific objectives of this research are:

- Determine the differential relative rotational benefits of winter and spring Brassicaceae oilseed species and cultivars within species on subsequent winter wheat production.
- Determine the effect of Brassicaceae oilseed crop species and cultivars within species on subsequent winter wheat grain quality.

4.3 Materials and Methods

4.3.1 *Site and trial specifications*

Field trials were planted at two locations (Moscow and Genesee) in the fall of 2012, 2013 and 2014. The University of Idaho Parker Research Farm, Moscow, ID (46° 43' N 116° 57' W) had an average yearly precipitation of 55 cm and had a Palouse silt loam soil type with a 0-3% slope. The University of Idaho Kambitsch Research Farm, Genesee, ID (46° 55' N, 116° 92' W) had a yearly precipitation of 45 cm and a Naff Palouse silt loam that is common throughout the region.

Specific details of crop and trial management of the Brassicaceae oilseed crop years can be found in Chapter 2 (winter species/cultivars) and Chapter 3 (spring species/cultivars), and are not repeated here.

After harvesting the Brassicaceae oilseed crops, the complete trial area was cultivated and planted to a uniform crop of SY Ovation (fall of 2013) or WB.1529 (fall 2014) although the specific trial area was mapped and plots within the wheat allocated to the specific Brassicaceae crop in the previous season (Table 4.1).

Pre-plant cultivation and tillage was specific to the standard farming practices used at either Moscow or Genesee farms. At the Moscow location the Brassicaceae trial area was mowed and harrow tilled before being planted to winter wheat using a Great Plains double disc opener planter, set at 14 cm row spacing. At Genesee the trial area was direct seeded into the standing previous Brassicaceae crop residue, using a JD single disc no-tillage drill, and row spacing set at 25 cm spacing.

Winter wheat seeding rates were constant with a target seeding rate of 2,000,000 seeds ha^{-1}. All seed was treated with Dividend Extreme® (difenoconazole, mefenoxam) fungicide. Planting depth was uniform across individual trials and set at 2.5 cm.

Soil tests were carried out prior to planting winter wheat and fertility managed according to the standard practice at each location according to average annual precipitation (Table 4.1).

4.3.2 *Experimental design*

The experimental design was a randomized complete block with one winter wheat variety planted uniformly over the following: (1) winter Brassicaceae oilseed crops planted at Moscow in 2012-2013 and Genesee in 2013-2014, with 6 cultivars from 3 species, and 4 replicates; and (2) spring Brassicaceae oilseed crops planted at Moscow in 2013 and 2014, and Genesee in 2014, with 12 cultivars from 6 species, and 4 replicates.

4.3.3 *Data collected*

Winter wheat emergence was assessed visually on a 1-9 scale of increasing emergence with 1 being complete crop failure and 9 being uniform emergence across the plot area. Visual evaluations were taken for wheat yellow strip rust (*Puccinia striiformis*), in the early staged of disease development, thereafter rust was controlled through foliar fungicide application. Plant height was recorded after heading, and heads (tillering) were counted over a uniform 1 m row. None of these traits measured showed any differences between treatments (previous Brassicaceae cultivar) and data is not presented in the Results section.

At maturity plots were harvested according to the previous Brassicaceae oilseed crop and yield determined. Post-harvest quality factors included: test weight; grain protein; flour yield; break flour yield, and cookie diameter. Sub-samples of seed taken from each plot were tested by the University of Idaho Wheat Quality laboratory in Aberdeen, Idaho.

4.3.4 *Data analysis*

Data was analyzed using a general linear model, and Duncan's multiple range tests (SAS, 2009). All computations were carried out using the Statistical Analysis Software (SAS, 2009) program for the entire data set. Wheat performance after spring and winter Brassicaceae crops were analyzed separately as there was severe confounding between spring and winter trials.

4.4 Results

Means squares from the winter Brassicaceae analyses of variance of wheat yield, wheat gross return, Brassicaceae crop yield, Brassicaceae crop return, and combined gross return showed significant differences in wheat yield and gross returns between environments (years and sites). Despite wheat yield after Wichita (*B. napus*) being highest at 3,775 kg ha^{-1} and *C. sativa*, cultivar Joelle being lowest at 3,327 kg ha^{-1}, there were no significant differences in wheat yield or gross return following the oilseed crop cultivars or species (Table 4.2). As expected from Chapter 2, there were significant differences in Brassicaceae seed yield and in oilseed crop returns. The highest oilseed yield was obtained from Wichita *B. napus* with 2,969 kg ha^{-1} followed by Amanda with 2,771 kg ha^{-1}, and this in turn was reflected in oilseed crop gross returns. Overall 2-year crop returns mirrored the same pattern as oilseed crop returns. The highest 2-year crop returns from the winter oilseed crop-winter wheat rotation was achieved from planting winter *B. napus* followed by winter wheat and these returns were significantly higher than either *B. rapa*-winter wheat or *C. sativa*-winter wheat.

Means squares from the winter Brassicaceae analyses of variance of grain protein, flower yield, break flower yield and cookie diameter showed significant environmental impacts on all grain quality, but only break flour yield showed significant differences between previous oilseed crops (Table 4.4). Winter wheat following *C. sativa* cultivar Joelle were significantly higher for break flour yield (43 %) than wheat following the old *B. napus* rapeseed cultivar Dwarf Essex (41.2 %). However, interpretation of this somewhat slight difference is difficult.

Means squares from the analyses of variance of wheat yield, wheat gross return, Brassicaceae crop yield, Brassicaceae crop return, combined gross return for spring Brassicaceae rotation are presented in Table 4.6. Environmental differences were highly significant for all yield and economic factors. Winter wheat yield after the different spring Brassicaceae oilseed crops ranged from a high of 8,923 kg ha^{-1} for Oasis (*B juncea*) to a low of 8,386 kg ha^{-1} for *B. carinata* cultivar 0808146M, but there were no significant differences in wheat yield (and not surprisingly) wheat gross return after any of the spring Brassicaceae oilseed (Table 4.7). As expected from the seed yield of spring oilseed crops in Chapter 3, there were significant differences in yield and gross return of the different Brassicaceae oilseed crops. Highest oilseed yield was obtained from the hybrid *B. napus* cultivar DKL-3042.RR followed by *B. juncea* cultivar Oasis 2,414 kg ha^{-1} and *B. napus* cultivar Empire. Gross returns between Brassicaceae crops varied with their respective price similar, but different yields. Pacific Gold offered the highest combined gross return to the farmer because of its high yield and high price as a condiment spice. The oilseed crop yield and potential oilseed crop returns were contributing factors in the significant 2-year gross returns of oilseed crop-winter wheat crop observed.

Means squares from the spring Brassicaceae analyses of variance of grain protein, flower yield, break flower yield and cookie diameter showed significant environmental differences for all quality traits but only grain protein showed significant differences between previous oilseed crops (Table 4.8). Winter wheat following *S. alba* cultivar Tilney had the highest grain protein (10.0%), while lowest grain protein was following *B. napus* cultivar Empire (9.2).

4.5 Conclusions and Recommendations

Winter wheat following six different winter Brassicaceae crops from three species showed no significant differences in seed yield, and hence wheat gross returns. The highest 2-year oilseed crop-winter wheat, crop returns was from the most productive oilseeds *B. napus* Wichita or Amanda. There was no significant difference in winter wheat quality following these winter Brassicaceae.

Similar results were obtained when winter wheat productivity and quality were examined following spring Brassicaceae oilseed crops, with no significant yield differences in winter wheat production or grain quality. Crop prices are continuously fluctuating and it is difficult to provide conclusive economic returns year-after-year. However, over the time period of these trials, the highest gross 2-year crop return to the grower, were achieved by planting *B. juncea* condiment mustard cultivar Pacific Gold, due perhaps to a high seed value. *Brassica napus* crops (particularly in this study DKL-3042.RR) and the *B. juncea* cultivars showed greatest promise as spring biofuel feedstocks crops. However, both canola and condiment spice are food crops, and high canola and condiment mustard prices may limit their practical use as low cost biofuel feedstock oils.

Locations chosen for the trials have been managed by the University of Idaho and have been in what might be considered as a diverse crop rotation, in comparison to the traditional PNW rotations which are more predominantly wheat. It may be reasonable to assume that greatest rotational effects will be observed in situations which would benefit from broader crop rotations. If this is true, then in different environments with less variation in crop rotation the impact of the different oilseed crops on following productivity may have been greater that observed in this study, and perhaps subsequent wheat crop would see a greater impact from the introduction of Brassicaceae crops. Although there is little or no evidence of this from past research, it may provide an opportunity for future studies.

When producers consider maximizing their rotational crops the interaction from the previous to the subsequent crop may be a decisive factor. However, the subsequent yield of two different wheat varieties at two different environments over two years showed no significant difference related to previous oilseed crop.

Overall conclusion and recommendation is that if growers (or indeed an oilseed industry) aim to produce Brassicaceae crops in rotation with winter wheat in the PNW environment, it is clear the most productive winter *B. napus* oilseeds offer an attractive option in the crop-fallow regions, and spring *B. napus* or *B. juncea* oilseed in the higher rainfall continuous cropping regions.

4.6 References

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Table 4.1. Growing conditions of winter wheat planted after spring and winter Brassicaceae oilseed crops at Moscow and Genesee in 2013-2014 and 2014-2015.

Site	Year	Brassica	Wheat Cultivar	Plant Date	Fertility	Post Plant Chemicals
Moscow	2013-2014	Spring	SY Ovation	20-Oct-13	Pre-Plant 275 kg ha^{-1} 31:10:0:6.6 Top dressed 45 kg ha^{-1} N and 6.7 kg ha^{-1} S	April 30, 2014: Huskie 877 mL ha^{-1}, Quilt 512 mL ha^{-1}, Affinity BroadSpec 58.5 mL ha^{-1}, Axial XL 1198 mL ha^{-1}.
Moscow	2013-2014	Winter	SY Ovation	20-Oct-13	Pre-Plant 275 kg ha^{-1} 31:10:0:6.7 Top dressed 45 kg ha^{-1} N and 6.7 kg ha^{-1} S	April 30, 2014: Huskie 877 mL ha^{-1}, Quilt 512 mL ha^{-1}, Affinity BroadSpec 58.5 mL ha^{-1}, Axial XL 1198 mL ha^{-1}.
Moscow	2014-2015	Spring	WB-1529	17-Oct-14	Pre-Plant 275 kg ha^{-1} 31:10:0:6.8. Top dressed 47.2 kg ha^{-1} N and 9.6 kg ha^{-1} S	April 12, 2015. Huskey pyrasulfotole, bromoxynil octanoate, bromoxynil heptanoate (broadleaf) 877 mL ha^{-1}; Affinity Broadspec thifensulfuron-methyl, tribenuron-methyl (broadleaf) 585 mL ha^{-1}; Axial XL pinoxaden (wild oat) 1198 mL ha^{-1}; Priaxor fluxapyroxad, pyraclostrobin (fungicide) 292 mL ha^{-1}.
Genesee	2014-2015	Spring	WB-1529	19-Oct-14	Pre-Plant 45.3 kg ha^{-1} 40:0:0:6. Top dressed 45 kg ha^{-1} N and 6.7 kg ha^{-1} S	April 20, 2015. Huskey pyrasulfotole, bromoxynil octanoate, bromoxynil heptanoate (broadleaf) 877 mL ha^{-1}; Affinity Broadspec thifensulfuron-methyl, tribenuron-methyl (broadleaf) 585 mL ha^{-1}; Axial XL pinoxaden (wild oat) 1198 mL ha^{-1}; Priaxor fluxapyroxad, pyraclostrobin (fungicide) 292 mL ha^{-1}.
Genesee	2014-2015	Winter	WB-1529	19-Oct-14	Pre-Plant 45.3 kg ha^{-1} 40:0:0:6. Top Top dressed 45 kg ha^{-1} N and 6.7 kg ha^{-1} S	April 20, 2015. Huskey pyrasulfotole, bromoxynil octanoate, bromoxynil heptanoate (broadleaf) 877 mL ha^{-1}; Affinity Broadspec thifensulfuron-methyl, tribenuron-methyl (broadleaf) 585 mL ha^{-1}; Axial XL pinoxaden (wild oat) 1198 mL ha^{-1}; Priaxor fluxapyroxad, pyraclostrobin (fungicide) 292 mL ha^{-1}.

Table 4.2. Mean squared from the analyses of variance of winter wheat seed yield, gross return on winter wheat crop, previous winter Brassicaceae oilseed crop seed yield, previous winter Brassicaceae oilseed crop gross return, and combined gross return (winter Brassicaceae crop and winter wheat crop) presented as average return year^{-1}.

Source	[a]d.f.	Wheat yield	Wheat gross return	Brassicaceae crop yield	Brassicaceae crop return	Combined gross return
Environment	1	8,769,735 ***	143,757 ***	12,570,627 ***	665,599 ***	21,189 **
Error (1)†	6	86,445 n.s.	807 n.s.	838,980 **	39,580 **	4,847 **
CV	5	181,163 n.s.	1,900 n.s.	4,609,333 ***	526,294 ***	63,244 ***
CV x Environment	5	121,612 n.s.	1,106 n.s.	1,975,172 ***	89,367 ***	8,331 **
Error (2)†		143,706	1,410	161,994	8,000	1,363

[a]d.f. = degrees of freedom
*=0.01<P<0.05;**=0.01>P>0.001;***=P<0.001; n.s.= not significant
† Error (1) = replicates within environments; Error (2) = Pooled replicate error.

Table 4.3. Winter wheat seed yield, gross return on winter wheat crop, previous winter Brassicaceae oilseed crop seed yield, previous winter Brassicaceae oilseed crop gross return, and combined gross return (winter Brassicaceae crop and winter wheat crop) presented as average return year^{-1}.

Species	CV	Wheat yield	Wheat gross return	Brassicaceae crop yield	Brassicaceae crop return	Combined gross return
		---kg ha^{-1}---	-\$ ha^{-1} -†	---kg ha^{-1}---	-\$ ha^{-1} -‡	-\$ ha^{-1} -‡‡
B. napus	Amanda	3,648	401	2,771 ^{ab}	637 ^{ab}	346 ^{a}
	Durola	3,693	405	2,493 ^{b}	573 ^{b}	326 ^{a}
	Dwarf Essex	3,421	374	2,596 ^{ab}	597 ^{ab}	324 ^{a}
	Wichita	3,725	407	2,969 ^{a}	683 ^{a}	363 ^{a}
B. rapa	Largo	3,470	385	1,752 ^{c}	201 ^{c}	195 ^{b}
C. sativa	Joelle	3,377	374	959 ^{d}	74 ^{d}	149 ^{c}
	Mean	3,556	391	2,257	461	284
	s.e.	n.s.	n.s.	142.30	31.62	13.05

† = Wheat price at \$156.40 kg^{-1} (\$5.75 bu);
‡ = Crop prices set as of November 1st 2015 Chicago Board of Trade. Whereby: *B. napus* (canola) @\$0.396 per kg^{-1}; *B.rapa* @\$0.396 per kg^{-1}; *C.sativa*@\$0.132 per kg^{-1}.
‡‡ = combined price of † and ‡.
Cultivar means within columns with different superscript letters are significantly different (P>0.05), according to Duncan's multiple range test; n.s. = no significant cultivar differences.

Table 4.4. Mean squared from the analyses of variance of winter Brassicaceae prior to winter wheat seed quality, protein, flower yield, break flower yield, and cookie diameter presented as average return year^{-1}.

Source	[a]d.f.	Protein	Flower Yield	Break Flower Yield	Cookie
Environment	1	1.60167 n.s.	0.00489 n.s.	162.884 ***	0.79475 ***
Error (1)†	2	0.20833 n.s.	0.02446 n.s.	7.93083 **	0.00105 n.s.
CV	5	0.42967 n.s.	0.55993 n.s.	0.88322 n.s.	0.01851 n.s.
Environment *CV	5	0.16167 n.s.	0.29053 n.s.	0.44263 n.s.	0.01722 n.s.
Error (2) †		0.59033	1.49163	0.47571	0.01929

[a]d.f. = degrees of freedom
*= 0.01<P<0.05;** = 0.01>P>0.001;*** = P<0.001; n.s.= not significant
† Error (1) = replicates within environments; Error (2) = Pooled replicate error.

Table 4.5. Winter wheat seed protein, flower yield, break flower yield, and cookie diameter following previous winter Brassicaceae oilseed crop presented as averages.

Species	CV	Protein	Flower Yield	Break Flower Yield		Cookie
		---%--	---%--	---%--		---cm--
B. napus	Amanda	8.4	66.5	42.2	ab	9.01
	Dwarf Essex	8.1	66.0	41.6	b	9.09
	Durola	8.6	66.7	42.8	ab	9.08
	Wichita	8.5	65.9	42.1	ab	8.96
B. rapa	Largo	8.6	65.7	42.1	ab	9.01
C. sativa	Joelle	9.1	66.1	42.8	a	8.91
	Mean	9	66	42		9.0
	s.e.	n.s.	n.s.	0.345		n.s.

Cultivar means within columns with different superscript letters are significantly different (P>0.05), according to Duncan's multiple range test; n.s. = no significant cultivar differences.

Table 4.6. Mean squared from the analyses of variance of winter wheat seed yield, gross return on winter wheat crop, previous spring Brassicaceae oilseed crop seed yield, previous spring Brassicaceae oilseed crop gross return, and combined gross return (spring Brassicaceae crop and winter wheat crop) presented as average return year^{-1}.

Source	[a]d.f.	Wheat yield	Wheat gross return	Brassicaceae crop yield	Brassicaceae crop return	Combined gross return
Environment	2	172,102,759 ***	351,977 ***	8,473,653 ***	124,462 ***	50,234 ***
Error (1)†	9	1,358,265 *	3,256 n.s.	334,930 n.s.	7,170 n.s.	3,470 *
CV	11	427,412 n.s.	1,145 n.s.	1,524,998 ***	102,143 ***	26,385 ***
CV x Environment	22	379,505 n.s.	1,009 n.s.	735,670 ***	11,109 **	3,202 **
Error (2)†		677,937	1,719	200,127	3,938	1,150

[a]d.f .= degrees of freedom

*= 0.01<P<0.05;** = 0.01>P>0.001;*** = P<0.001; n.s. = not significant

† Error (1) = replicates within environments; Error (2) = Pooled replicate error.

Table 4.7. Winter wheat seed yield, gross return on winter wheat crop, previous spring Brassicaceae oilseed crop seed yield, previous spring Brassicaceae oilseed crop gross return, and combined gross return (spring Brassicaceae crop and winter wheat crop) presented as average return year^{-1}.

Species	CV	Wheat yield	Wheat gross return	Brassicaceae crop yield	Brassicaceae crop return	Combined gross return
		---kg ha^{-1}---	-\$ ha^{-1} -†	---kg ha^{-1}---	-\$ ha^{-1} -‡	-\$ ha^{-1} -‡‡
B. carinata	0808146M	8,386	449	2,138 [bcd]	246 [de]	343 [ef]
	AAC-A110	8,769	468	1,896 [cde]	218 [de]	345 [ef]
B. juncea	Oasis	8,923	473	2,414 [b]	278 [cd]	377 [cd]
	Pacific Gold	8,798	468	2,267 [bc]	464 [a]	465 [a]
B. napus	DKL-3042.RR	8,857	468	2,877 [a]	331 [bc]	399 [bc]
	Empire	8,605	458	2,399 [b]	276 [cd]	368 [de]
	Gem	8,394	444	1,924 [cde]	246 [de]	346 [def]
	InVigor.L130	8,587	454	2,201 [bc]	253 [de]	353 [def]
B. rapa	Eclipse	8,615	459	1,741 [de]	200 [e]	326 [f]
C. sativa	CO.466	8,698	464	2,195 [bc]	84 [f]	274 [g]
S. alba	IdaGold	8,530	456	1,727 [de]	375 [b]	416 [b]
	Tilney	8,891	474	1,647 [e]	358 [b]	415 [b]
	Mean	8,626	458	2,223	232	344
	s.e.	n.s.	n.s.	134.88	18.92	10.30

† = Wheat price at \$156.40 kg^{-1}(\$5.75 bu);
‡ = Crop prices set as of November 1st 2015 Chicago Board of Trade. Whereby: *B. carinata* @\$0.396 kg^{-1}; *B. juncea* @\$0.704 kg^{-1}; *B. napus* (canola)@ \$0.396 kg^{-1}; *B.rapa* @\$0.396 kg^{-1}; *C.sativa* @\$0.132 kg^{-1}; *S. alba* @\$0.748 kg^{-1}; *B.juncea* (canola 'Oasis') @\$0.396 kg^{-1}; *B.napus* (rapeseed 'Gem') @\$0.44 kg^{-1}.
‡‡ = combined price of † and ‡.
Cultivar means within columns with different superscript letters are significantly different (P>0.05), according to Duncan's multiple range test; n.s. = no significant cultivar differences.

Table 4.8. Mean squared from the analyses of variance of spring Brassicaceae prior to winter wheat seed quality, protein, flower yield, break flower yield, and cookie diameter presented as average return year^{-1}.

Source	[a]d.f.	Protein	Flower Yield	Break Flower Yield	Cookie
Environment	2	58.5738 ***	0.33205 n.s.	170.004 ***	0.59113 ***
Error (1)†	3	2.36393 ***	0.95623 n.s.	0.88822 n.s.	0.01369 n.s.
CV	11	0.56099 **	0.64414 n.s.	1.43371 n.s.	0.01211 n.s.
Environment *CV	22	0.39671 **	0.79107 n.s.	1.46671 n.s.	0.01092 n.s.
Error (2) †		0.21229	0.67348	0.90607	0.01385

[a]d.f . =degrees of freedom
*= 0.01<P<0.05;** = 0.01>P>0.001;*** = P<0.001; n.s.= not significant
† Error (1) = replicates within environments; Error (2) = Pooled replicate error.

Table 4.9. Winter wheat seed protein, lower yield, break flower yield, and cookie diameter following previous spring Brassicaceae oilseed crop presented as averages.

Species	CV	Grain Protein		Flower Yield	Break Flower Yield	Cookie diameter
		---%--		---%--	---%--	---cm--
B. carinata	0808146M	9.10	e	66.1	40.5	8.94
	AAC-A110	9.56	bcde	65.9	40.8	8.86
B. juncea	Oasis	9.72	bcde	66.0	40.4	8.86
	Pacific Gold	9.93	abc	66.1	40.2	8.84
B. napus	DKL-3042.RR	9.70	bcde	66.3	40.4	8.85
	Empire	9.25	de	67.0	41.1	8.81
	Gem	9.33	cde	66.3	40.6	8.92
	InVigor.L130	9.62	bcde	65.8	40.2	8.85
B. rapa	Eclipse	9.80	bcd	65.9	39.8	8.82
C. sativa	CO.466	9.38	cde	65.9	39.4	8.84
S. alba	IdaGold	9.27	de	65.7	40.3	8.80
	Tilney	10.02	ab	66.1	41.1	8.79
	Mean	10		66	40	8.8
	s.e.	0.189		n.s.	n.s.	n.s.

Cultivar means within columns with different superscript letters are significantly different (P>0.05), according to Duncan's multiple range test.
n.s. = not significant.

Chapter 5: Conclusion and Recommendations

5.1 Winter Brassicaceae crops

For a crop to be considered a potential candidate for producing biofuel feedstock it must combine high yield and high seed oil content. Oil yield will ultimately determine the potential biofuel producing capacity, but this must combine high seed yield to ensure growers are suitably compensated for producing the crops. Additionally these crops must have adaptability and agronomic support in addition to the infrastructure needed for its production.

Brassica napus winter canola cultivar Wichita showed the highest potential in terms of yield with an overall average of 3,658 kg ha^{-1}, and with good seed oil content (413.1 g kg^{-1}), producing over 1,800 l ha^{-1} of feedstock oil. Amanda winter canola also performed consistently with, high seed yield and oil content. Amanda has been developed to be adapted to the PNW environment and local growers in the area are already familiar with it which may give it an advantage for rapid adoption by growers. In addition Amanda had better winter-hardiness that Wichita, which may offer better long-term stability over years in our northern climate. Also worth noting, the highest oil content was from the winter rapeseed cultivar Durola (445 g kg^{-1}). *Brassica rapa* cultivar Largo had an average yield of 1,852 kg-ha^{-1} and was lower yielding than all of the *B. napus* cultivars. Early maturity and resistance to seed pod shatter may give this cultivar/species greater potential in the hotter, drier regions, although the potential for *B. rapa* may be lower than that for *B. napus* in our experimental environment.

Joelle (*C. sativa*) had the lowest seed yield, seed oil content, lowest oil yield and was most intolerant to winter damage, at times causing total crop failure or loss. Joelle did produce a competitive yield at Genesee in 2013-2014 (2,166 kg ha^{-1}). In the case of winter camelina, its lack in stability of performance would make it an unwise choice to base a biofuel industry, where constant yields will be necessary. Working with the crop was frustrating, and in my personal opinion I think it retains too much of its weedy characteristics. I additionally observed its maturity lack uniformity.

5.2 Spring Brassicaceae crops

Combining seed yield and oil content gives a species potential as a biofuel feedstock. For spring *B. napus*, particularly the hybrid cultivar DKL-3042.RR which produced 795 l ha^{-1} (88 gal $acre^{-1}$), and the *B. juncea* cultivars Oasis 636 l ha^{-1} (~70 gal $acre^{-1}$) and Pacific Gold 617 l ha^{-1} (~68 gal $acre^{-1}$) have the best potential. Least potential as biofuel feedstock crops would be the low oil content *S. alba* cultivars with only 318 l ha^{-1} (35 gal $acre^{-1}$) for IdaGold and 327 l ha^{-1} (36 gal $acre^{-1}$) Tilney, or the *B. carinata* cultivars which each produced only 456 l ha^{-1} (50 gal $acre^{-1}$). This reflects the breeding objectives for these species as condiments, purposely lacking oil content congruent with its target end use being seed meal. *Camelina sativa* cultivar CO.466 did relatively well producing 570 l ha^{-1} (63 gal $acre^{-1}$) which although markedly lower than *B. napus* or *B. juncea* may have potential in the hotter and drier regions of the PNW.

The most productive plants have the best potential for being adopted as alternative spring crops. Highest seed yield was obtained from the hybrid *B. napus* cultivars DKL-3042.RR (1,676 kg ha^{-1}), InVigor.L130-LL (1,460 kg ha^{-1}), Pacific Gold (1,450 kg ha^{-1}), and CO.466 (1,435 kg ha^{-1}), while lowest seed yield was from the two *B. carinata* cultivars

AAC-A110 (1,019 kg ha^{-1}) and 0808146M (1,211 kg ha^{-1}), the two *S. alba* cultivars IdaGold (1,031 kg ha^{-1}) and Tilney (1,070 kg ha^{-1}), and *B. rapa* cultivar Eclipse (1,043 kg ha^{-1}). Producers must not forsake the values of these species in the condiment market.

The *Brassica* crops we tested, all offer an advantage in that they allow a change in the growing cycle that can be used to a producers advantage. If any *B. carinata* cultivars are going to be produced on a large scale in this region, more adapted (specifically earlier flowering) varieties specific to local growing conditions are need. *Brassica juncea* cultivars tended to be earlier than the other species and in general performed well; Pacific Gold has been produced in this area giving it an advantage as it is well adapted and produces acceptable yield. These factors may make it an option as an alternative spring planted Brassicaceae. *Brassica napus* cultivars all had similar characteristics. All *B. napus* entries experience some lodging, days to 50% flowering in *B. napus* cultivars was around 48 d, however, InVigor.L130-LL flowered later and had less lodging problems. *Brassica napus* has productive adapted cultivars and lots of genetic variation for future breeding efforts. *Brassica rapa* had reasonable, yet moderate pre harvest characteristics, however it flowered very early which may be an advantage in some environments. CO.466 (*C. sativa*) had very different morphology compared to all other entries in the trial, it also had some issues with shattering and uniform maturity. Grower acceptance may be a hurdle for *C. sativa* to overcome for it to have more production and it would need additional extension and outreach. Both *S. alba* cultivars flowered very early; IdaGold also showed higher average seedling survival, crop establishment, and taller plant height compared to Tilney. The value of this crop as a condiment should not be underestimated. Developing a better understanding of LAI for these cultivars may offer more effective tools for future cultivar selection.

5.3 Rotational impact on subsequent wheat

Examining the differential rotational impact of these spring- and fall-planted Brassicaceae oilseed crops on subsequent winter wheat production was very challenging. Despite wheat yield after Wichita (*B. napus*) being highest at 3,775 kg ha^{-1} and *C. sativa* cultivar Joelle being lowest at 3,327 kg ha^{-1}, there were no significant differences in wheat yield of gross return following the oilseed crop cultivars or species (Table 4.2). Winter wheat yield after the different spring Brassicaceae oilseed crops ranged from a high of 8,923 kg ha^{-1} for Oasis (*B juncea*) to a low of 8,386 kg ha^{-1} for *B. carinata* cultivar 0808146M, there were no significant differences in wheat yield & wheat gross return after any of the spring Brassicaceae oilseed.

Crop returns mirrored the same pattern as oilseed crop returns. Winter *B. napus* followed by winter wheat returns were significantly higher than either *B. rapa*-winter wheat or *C. sativa*-winter wheat. Spring planted Pacific gold offered the highest combined gross return to the farmer because of its high yield and high price as a condiment spice.

Quality impacts were difficult and often subtle, however, winter wheat following *C. sativa* cultivar Joelle were significantly higher in break flower (43 %) than that following the old *B. napus* rapeseed cultivar Dwarf Essex. Interpretation of this somewhat slight difference is difficult and may have to do with Joelle's inability to perform through the winter leaving the plot without plants through the year gaining additional water. Winter wheat following spring planted *S. alba* cultivar Tilney had the highest grain protein (10.0%), while lowest grain protein was following *B. napus* cultivar Empire (9.2).

5.4 Summary

A large proportion of dry land agriculture in the PNW is dominated by winter wheat and few alternative crops are available that have adaptability or profitability potential. The major conclusions from this research were that winter canola and winter rapeseed did show high yield and high biofuel feedstock potential with over 1,800 l ha^{-1} (~201 gal a^{-1}), which is greater than most other oilseed crops available. Current canola and rapeseed seed prices fluctuate continually but is highly competitive with winter wheat in today's market. Additional, rotational benefits of including these crops in rotation with winter wheat may increase the value of them and the sustainability of PNW agriculture. Future breeding research will likely continue to produce genetically superior cultivars with better adaptability for commercial production. Breeding for higher yield and oil content, oil quality, disease and insect resistance will most likely be necessary to meet challenges ahead. Additional grower resources and marketing will be essential to productive and widespread oil feedstock production in the Pacific Northwest.

For biofuel seed-stock oil production potential, hybrid oil producing spring *B. napus* crops, (particularly in this study DKL-3042.RR) showed the greatest promise. Similar to the findings of winter crops, spring *B. napus* cultivars, particularly the high yielding hybrid cultivars (DKL-3042.RR and InVigor.L130-LL) and *B. juncea* cultivars have the greatest potential as biofuel feedstock production. The *B. juncea* cultivars are more stress tolerant (heat and drought) and may have greater potential in the intermediate rainfall regions of the PNW (28 to 34 cm precipitation) where traditional spring canola and rapeseed can experience yield loss due to high temperature and drought stress at flowering and grain fill and may have greater potential in stress situations which adversely impact *B. napus* cultivars. *Brassica carinata* cultivars showed little or no adaptability in the PNW and have no potential as biofuel feedstock crops. Similarly, *S. alba* cultivars have little potential as biofuel feedstock crops unless the seed meal can be utilized for high value, for example as a pesticide.

When producers consider maximizing their rotational crops the interaction from the previous to the subsequent crop may be a decisive factor. However, the subsequent yield of two different wheat varieties at two different environments over two years showed no significant difference related to previous oilseed crop. Winter wheat following six different winter Brassicaceae crops from three species showed no significant differences in seed yield, and hence wheat gross returns. The highest 2-year oilseed crop-winter wheat, crop returns was from the most productive oilseeds *B. napus* Wichita or and Amanda. There was no significant difference in winter wheat quality following these winter Brassicaceae. Similar results were obtained when winter wheat productivity and quality were examined following spring Brassicaceae oilseed crops, with no significant yield differences in winter wheat production or grain quality. In different environments with less variation in crop rotation the impact of the different oilseed crops on following productivity may have been greater that observed in this study and perhaps subsequent wheat crop would see a greater impact from the introduction of Brassicaceae crops. This may be an opportunity for future research to examine.

To compare the potential of winter *versus* spring Brassicaceae oilseed crops depends on how you work their strengths into ones management system. Winter crops are more productive: however, this high yield is realized over two years to account for the fallow year. The PNW region does, however, have considerable hectares of crop-fallow land available and in these situations it would be winter canola or rapeseed which offers greatest production potential and grower profit. It was thought that camelina could offer an opportunity to eliminate one fall year out of two (i.e. rather than wheat-fallow-wheat-fallow use wheat-camelina-wheat-fallow), but preliminary studies (Brown, *pers comm*) show severe yield reductions in winter wheat following camelina compared to winter wheat following fallow. Spring crops offer an attractive broadleaf alternative crop for producers where herbicide tolerant cultivars and breaking pest and weed cycles can offer many grower benefits. The variable growing environments that exists in the PNW points to a need for both winter and spring planted *Brassica* crops; winter crops in the drier crop-fallow region and spring crops in the higher rainfall continuous cropping areas.

Overall conclusion and recommendation is that if growers (or indeed an oilseed industry) aims to produce Brassicaceae crops in rotation with winter wheat in the PNW environment, it is clear the most productive winter *B. napus* oilseeds offer an attractive option in the crop-fallow regions and spring *B. napus* or *B. juncea* oilseed have greatest potential in the higher rainfall continuous cropping regions.