AN ABSTRACT OF THE THESIS OF

Brock T. Ferguson for the degree of Master of Science in Crop Science presented on March 19, 2015

Title: Spring Nitrogen and Cultivar Effects on Winter Canola (*Brassica napus* L.) Production in Western Oregon.

Abstract approved:

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Thomas G. Chastain

Limited information is available on the effects of applied spring nitrogen (N) and cultivar on winter canola (*Brassica napus* L.) production in high-rainfall environments. The objectives of this investigation were: (i) to determine the effects of spring N and winter canola cultivars on seed and oil production characteristics, and (ii) to ascertain the influence of spring N and winter canola cultivars on dry matter partitioning and expression of seed yield components. Field trials for both objectives were conducted over a three-year period at Corvallis, Oregon with four spring N application rates: 0, 56, 112, and 156 kg N ha^{-1}.

Four winter canola cultivars were used (Athena, Baldur, Virginia and Kronos) to study spring N effects on seed and oil production characteristics. Lodging severity determined seed yield responses to spring-applied N. Under low or moderate lodging severity, yield was increased in proportion to spring N rate. When lodging was severe, yields were reduced by application of 168 kg N ha^{-1}. Yield increases attributable to spring N ranged up to 75% while losses under lodged conditions ranged up to 11%. Seed number m^{-2} was the main contributor to increased or decreased yields observed in

response to spring N. Seed oil content was largely reduced by increased N rate, but seed protein was unaffected. Oil yield was increased by spring applied N with low or moderate lodging but not when lodging was severe. Seed yield and seed weight varied among cultivars in each of the three years. Athena, Baldur, and Virginia averaged 2800 kg ha^{-1} with a different cultivar producing the highest average yield each year while Kronos consistently yielded the lowest at 2550 kg ha^{-1}. Expression of seed yield by cultivars was governed by a combination of seed number and seed weight. The best spring N rate for winter canola was 112 kg N ha^{-1} because it provided high potential seed yield while minimizing the loss in yield associated with lodging.

Two winter canola cultivars (Athena, Baldur) were used to study effects of spring N on dry matter partitioning and expression of seed yield components. Dry matter partitioning and expression of seed yield components were differentially affected by lodging. Biomass tended to increase with spring N rate and with advancement in developmental stage except with severe lodging. Tissue N content was incrementally increased in proportion to spring N rate. Spring N had no effect on tissue C content except when lodged where C content declined with increasing N rate. Mixed results were observed with harvest index (HI); spring N rates > 56 kg N ha^{-1} caused reductions in HI in two years but no trend was evident in the third year. Racemes plant^{-1} were not affected by N except when lodged. Nitrogen rates $\geq$ 112 kg N ha^{-1} increased mainstem siliques raceme^{-1} by 36% in 2008 and by 39% in 2010, but not when lodged in 2009. Seed yield components varied in their contributions to yield, but mainstem siliques raceme^{-1} produced the most consistent effects on seed yield by increasing seed number m^{-2}. The

results of this study improve our understanding of winter canola production in a wet

environment.

Spring Nitrogen and Cultivar Effects on Winter Canola (*Brassica napus* L.) Production in

Western Oregon

by

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Brock T. Ferguson, Author

ACKNOWLEDGEMENTS

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1.1. What is Canola?

Two members of the genus *Brassica* are important oil seed crops; *B. napus* and *B. rapa*. These species are natives of Asia and Mediterranean countries but with cultivation, these species are now found around the world. Historically, these oil seed crop species were collectively known as rapeseed or oil seed rape. The original uses for the oils extracted from the seed of these species were as a fuel oil and for lubricants but were not very widely used as edible oil. A significant crop improvement program in Canada was successful in reducing the erucic acid content in the oil and glucosinolates content in the seed meal remaining after oil extraction (Downey and Rimmer, 1993). The development of low erucic acid content in the oil increased the appeal of the oil as an edible product for human consumption and the low glucosinolate in the meal made that product more attractive as livestock feed. The end result of this breeding program was given a new name – Canola, in recognition of the work done in Canada, and the concomitant low concentration of erucic acid (less than 20 g kg^{-1}) in the oil and low glucosinolates (less than 30 μmol g^{-1}) present in the seed meal.

The introduction of canola did not end the production of rapeseed and in fact, there are still industrial oil type cultivars with high concentration of erucic acid in the oil in cultivation today. The oil from these cultivars has value as lubricants, cosmetic products and in feedstocks for other industrial processes but are not suitable for human consumption. In addition, there are edible oil rape cultivars grown that have low erucic acid but have high glucosinolates in the meal. In Europe and in some other regions, the name canola is not used for oil seed rape cultivars that have both low erucic acid and low

glucosinolates. Both industrial rapeseed and edible oil rape/canola cultivars are used in the production of biodiesel.

Canola is one of the world's most important oil seed crops, ranking behind only soybean (*Glycine max* L.) in oil production. Since its development in 1974, canola has grown to account for 10-15% of the world-wide oil crop produced (Ash, 2012). Canola and other edible rapeseed oil production totaled over 23.6 million Mg (metric tons) in 2013 (FAO 2014). Total world-wide seed production of canola and edible rapeseed in 2013 was 65.1 million Mg and the crop was grown on 34 million hectares. Increases in global demand for edible oil products, biofuels, and other specialty applications have continued to spur demand for high-yielding oil seed crops like canola.

The oil is extracted from canola seed by crushing with either a cold-press or by expeller-pressing followed by solvent (hexane) extraction. Canola oil is low in saturated fats, and has health-promoting levels of omega-3 fatty acids. Not only is canola oil an attractive product, the seed oil content (40 to 49% by weight) is very high in comparison to other oil seed crops. The seed meal remaining after oil extraction is a high-protein source of livestock feed and a valuable by-product of canola production. The meal can also be used as a soil amendment because of the relatively high N and organic material content in the meal.

Canola has two primary types of cultivars based on growth habit – spring canola and winter canola. Spring canola cultivars are planted in late winter to early spring and can be either *B. napus* or *B.* rapa. Winter canola cultivars are planted in late summer or early fall and are almost exclusively *B. napus*. Spring canola cropping is well-suited for regions with cold winters such as the Northern Great Plains of North America because

winter hardiness is poor (Johnston et al., 2002). Winter canola cultivars are bred to take advantage of longer growing seasons in regions with mild winter climates such as the Pacific Northwest USA (Shafii et al., 1992). Winter canola crops in the Pacific Northwest can yield more than twice that of spring canola (Ehrensing, 2008). Oil concentration in the seed varies among cultivars and there are genotype x environment interactions that govern oil content – these are more evident in some regions than in others (Shafii et al., 1992).

The protein concentration in the seed is an important quality characteristic of the meal, a valuable by-product of the seed extraction process. Seed protein content in canola and winter oil seed rape has been reported to vary with applied N and can range from 180 to 280 g kg^{-1} (Rathke et al., 2005; Kutcher et al., 2005).

Seed yield of winter canola varies widely with climate, soils and other aspects of crop production potential. In central Germany, seed yields in winter oilseed rape trials ranged from 1700 kg ha^{-1} to 5250 kg ha^{-1} (Rathke et al., 2005). Winter canola trials conducted in Missouri and Texas, USA produced seed yields ranging from 2700 kg ha^{-1} to 3250 kg ha^{-1} (Conley et al., 2004). Preliminary trials with winter canola in western Oregon showed that seed yields ranged from 2706 to 5208 kg ha^{-1} (Chastain et al., 2006). One additional measure of canola crop productivity is oil yield. Oil yield is calculated as the product of seed yield and the fractional oil content of the seed.

Seed yield in canola/oil seed rape has increased over time as a result of better agronomic practices and genetic improvement but yield stability has not been improved appreciably in comparison to wheat (Rondanini et al., 2012). Nevertheless, stability of

seed yield in winter oilseed rape was strongly influenced by nitrogen fertilization (Boelcke et al., 1991).

1.2. Winter Canola Growth and Development

The BBCH (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) scale is used to identify the developmental stages of crops and is based on the Zadoks scale for cereals but has been standardized and extended to many other crops including canola (Lancashire et al., 1991). Depending on the date of planting, planting depth and the availability of seed zone water, winter canola seedlings typically emerge (BBCH 09) about one week after planting in western Oregon. The first-true leaf (BBCH 11) appears on the seedling plants at about 3 weeks after planting and development is driven by accumulated heat.

Depending on plant stand density, the canola plant can produce multiple branches (also known as side shoots) in addition to the mainstem – the oldest plant stem originating from the seedling shoot system. At low density, there are many branches and a mainstem and at high density, there are few branches and a mainstem. By mid-November with row spacing of 30 cm or less, the crop canopy closes because of the formation of leaves (BBCH 12-19) and branches (BBCH 20-29). At this time, the plants will be in the rosette stage with many leaves but no stems (BBCH 29). The rosette consists of larger/older underlying leaves topped by smaller younger leaves. The crop will remain quiescent over winter in this stage of development until late winter or early spring when average air temperature exceeds 5°C (Diepenbrock et al., 2000). Winter canola plants in eastern Oregon should have at least 6 leaves prior to overwintering in the dormant state (Wysocki et al., 2005).

Stem elongation, also known as bolting, typically begins around late February to early March depending on weather conditions at the rosette stage (BBCH 30). Stems elongate by sequential growth of the internode from BBCH 31 to 39. Elongation of the branches follow that of the mainstem. By convention, BBCH 40-49 (development of harvestable vegetative parts portion of the BBCH scale) are not monitored in oil seed rape and canola crops.

Canola has a branched inflorescence known as a raceme with flowers located on the short branches. The mainstem and branches produce flower buds that are initially enclosed by leaves. Flower buds first appear (BBCH 51) by late March in winter canola in western Oregon. The flower buds are formed within the raceme according to an acropetal chronological sequence from the base of the raceme to the apex (Wang et al., 2011). This pattern of development is found both on the raceme located on the mainstem and on the racemes located on branches. The expansion within each raceme from the central axis is by the short branches on which the flowers are borne follows a basipetal pattern. Development of the raceme and associated flower buds ceases at BBCH 59.

The first open flowers (BBCH 60) appear in the basal region of the raceme shortly after buds have completed formation in the apex of the raceme. Full flowering (BBCH 65) is reached in late April through early May. Pollination of *B. napus* oil seed crops can either be through self-pollination or cross-pollination with about 70% of the pollination taking place via self-pollination (McGregor, 1976). Although self-pollination predominates in the species (70%), seed yield has been shown to increase with the use of insect pollinators. The plant does encourage outcrossing by producing attractive flowers and nectar which attract insect pollinators. Honeybees (*Apis melifera* L.) are the primary

insect pollinators of canola and oil seed rape, as well as native bumble bees. Flowering ends at BBCH 69.

Once pollinated, seed filling takes place and the winter canola crop is ready for harvest in early July through mid-July. The fruit (and seed within) develop from ovaries on these short branches starting at BBCH 70. The fruit is known as a silique and is a type of pod having multiple ovules located within. Development of the silique (elongation of the silique and early seed development) follows the same acropetal sequence as mentioned previously for floral development and is complete at BBCH 79. Siliques start their growth at the end of flowering and reach maximum dry weight about 24 days later (Diepenbrock and Geisler, 1979). Siliques on the mainstem accumulate more dry matter than siliques produced on branches. During silique development, carbon and nutrients are partitioned to the developing seeds. Protein content is highest early in seed development but declines as the size of the seed increases and the oil concentration in the seed reaches a peak late in the seed development process.

Maturation of the seed and pod ripening takes place between BBCH 80 and 89. The maximum dry weight of canola seed is reached at physiological maturity (BBCH 80-81) when the siliques have begun to lose their green color but the seeds are not yet black (Elias and Copeland, 1991). Winter canola seeds attain maximum dry weight between 40 and 48 days after end of flowering and start of silique development (Diepenbrock and Geisler, 1979; Elias and Copeland, 1991). Seed harvest typically takes place at BBCH 85, prior to the time that siliques have fully ripened (50% ripe) but the seeds are black and hard. Seed water content at harvest is approximately 100 g kg^{-1}.

The pattern of dry matter (biomass) accumulation and partitioning in winter canola is similar to many other fall-planted annual crops that are harvested for seed in the following summer. Dry matter accumulation begins shortly after crop emergence in the fall but remains low relative to the final plant dry weight at maturity and ceases with cold weather in winter. While dry matter accumulation is low prior to cessation of growth in winter, this small amount plays an important role in the crop's ability to overwinter and successfully begin growth in spring (Velička et al., 2012). Moreover, about half of the nitrogen uptake by winter canola crop is complete by BBCH 30 (rosette stage) and precedes dry matter accumulation, thus the timing of N application is important (Wysocki et al., 2007). Nitrogen needs to be made available to the crop and sufficiently early so that it can be taken up to support this rapid growth (biomass accumulation) of the crop during stem elongation. Dry matter accumulation is greatest starting with stem elongation and continues at a high rate until reaching a peak at the start of silique ripening (BBCH 80).

Harvest index (HI) is a measure of dry matter partitioning in crops in relation to economic yield and has been defined in a number of ways depending on the crop and the nature of the research investigation. For the purposes of this study, HI is defined as the ratio of seed yield to total above-ground biomass at crop maturity. Harvest index has been reported to vary between 0.28 and 0.50 for winter oilseed rape in central Germany (Rathke et al., 2005). Svečnjak and Rengel (2006b) found that HI ranged from 0.11 to 0.18 in spring canola. Other reported values for HI in canola and oilseed rape range from 0.17 to 0.35 (Islam and Evans, 1994; Wright et al., 1995).

1.3. Seed Yield Components

The seed yield components in winter canola include plants area^{-1} (plant population or stand density), branches plant^{-1}, racemes plant^{-1} (or per branch), siliques raceme^{-1}, seeds silique^{-1}, and individual seed weight. Seed yield is the mathematical product of these components and the individual components can be expressed in several ways. The variation in seed yield and the relationship to yield components can often be simplified to two basic components; seed number area^{-1} and seed weight. Alternately, seed yield components in winter oil rapeseed or canola can be expressed as primary yield components and secondary yield components (Diepenbrock et al., 2000). Primary yield components are thought to have a direct effect on seed yield and include plants area^{-1}, siliques plant^{-1}, seeds silique^{-1}, and individual seed weight.

Seed yield components vary widely in their impact on seed yield in canola according to the literature. Several studies show that applied N increased seed yields in canola through greater numbers of siliques plant^{-1} rather than by increased seeds silique^{-1} or seed weight (Asare and Scarisbrick, 1995; Hocking et al., 1997; Svečnjak and Rengel, 2006b). Conversely, Wang et al. (2014) found that seeds silique^{-1} was increased by N application but not seed weight in oilseed rape in China. Nitrogen increased seeds silique^{-1}, and in turn, contributed to greater seeds m^{-2} and ultimately seed yield. Seed yield variation in winter oilseed rape in Germany did not appear to be related to the number of siliques plant^{-1}, seeds silique^{-1}, or the number of branches present on the plant (Ijaz and Hornermeier, 2012).

Habekotté (1993) found that both the number of siliques m^{-2} and seeds m^{-2} were related to the size of crop biomass during flowering in oilseed rape. This is a classical

source-sink relationship where the source is the biomass (photosynthetic capture system) and the sink is the developing siliques or seeds. Therefore, seed yield in canola is related to the size, architecture, and health of the plant canopy. Several studies indicate that seed yield of canola and oilseed rape is more limited by the source than by the availability of sinks including siliques, ovules, and seeds (Diepenbrock and Geisler, 1979; Habekotté, 1993; Wang et al., 2011; Weymann et al. 2015). To illustrate this source limitation, Wang et al. (2011) found that removal of either mainstem racemes or branch racemes increased the number of ovules silique^{-1}, seeds silique^{-1}, and siliques raceme^{-1} in the remaining racemes. Habekotté (1993) reported that current photosynthesis was more important than partitioning from reserves elsewhere in the plant as this remobilization accounted for at most 12% of seed yield.

Compensation for low seed weight in winter oilseed rape is often accomplished via increased seed number and therefore only a weak correlation has been shown to exist between seed weight and seed yield (Diepenbrock et al., 2000). Seed weight is the last seed yield component to complete development (Diepenbrock, 2000) and develops as dry matter is partitioned at various rates, depending on silique branch position, through approximately 50 days after flowering (Diepenbrock and Geisler, 1979).

1.4. Management of Winter Canola

Optimum stand establishment in canola requires good seed-to-soil contact. Before planting, a firm seedbed, free of large clods, should be prepared. The seedbed should not be worked too fine or packed too hard as this could result in crusting of the soil which may inhibit seedling emergence (Ehrensing, 2008). Using a roller for the last tillage pass will create an optimum seedbed for planting. Time to seed germination in the

field is dependent on several site-dependent factors including soil temperature and seed zone water content.

One limitation to the planting of winter canola in the Pacific Northwest is the potential for occasional poor stand establishment under dry fall conditions (Wysocki et al., 1991; Wysocki et al., 1992). Late plantings made to coincide with late arriving fall rains often have much lower seed yields than earlier plantings.

Several diseases are important in the production of winter canola, and two major fungal diseases in particular are problematic worldwide - Sclerotinia stem rot and blackleg (Ehrensing, 2008). Sclerotinia stem rot is caused by the fungus, *Sclerotinia sclerotiorum*, which weakens the stem causing lodging and premature ripening of the crop. Blackleg is caused by the fungus, *Phoma lingam* (*Leptosphaeria maculans*), which causes a wide range of disorders in the canola plant including leaf lesions, stem cankers, root rot, seedling dieback, stunting and wilting, and as a result, can reduce seed yield. The incidence of both diseases in canola varies from year to year and increased N rate can lead to greater incidence of the diseases (Kutcher et al., 2005). The incidence and severity of Sclerotinia stem rot and blackleg in winter canola and oil seed rape can be reduced with applications of certain fungicides (Ijaz and Hornermeier, 2012).

Harvesting canola seed can be done in three different ways. Canola can be swathed and then combined with a pickup attachment, or direct combined while still standing (Ehrensing, 2008). Harvesting at the correct maturity is critical. Harvesting too late increases seed loss due to shattering, while harvesting too early causes excessive green seed or reduced low oil content. Swathing the crop followed by timely combining will reduce the chance of yield loss due to shatter compared to direct combining. After

swathing the crop dries in a windrow before being picked up and threshed with a combine. Canola pushers can also be used to directional force lodge the crop instead of cutting with a swather. This allows the plants to ripen while lying flat and reduces the risk of random lodging and shattering. Plants are combined opposite the direction of pushing.

1.5. Nitrogen Management in Winter Canola

Nitrogen is typically the nutrient that most limits seed yield in canola production (Jackson, 2000; Rathke et al., 2005). Nitrogen is required by the canola plant for essential physiological activities such as photosynthesis (Gammelvind et al., 1996) but specifically for seed yield, N is needed to support canopy development associated with stem elongation in the spring, carbon capture by the canopy, and partitioning of fixed carbon to seed and the oil contained within. Tissue N content in canola declines from a high prior to stem elongation to a low at seed harvest (Hocking et al., 1997). Nitrogen recommendations for canola in Oregon are predicated on the expected yield of the crop, N requirement of the crop, soil available N, and cropping history (Wysocki et al., 2007).

Nitrogen application recommendations for winter canola production in Oregon have been based on trials conducted in the semi-arid eastern portion of the state (Wysocki et al., 2007). These trials revealed that the total requirement for N by the canola crop is 6.5-7.5 kg ha^{-1} per each 100 kg ha^{-1} in expected seed yield. Jackson (2000) found that the total N requirement for spring canola in Montana, USA was about 200 kg N ha^{-1} or about 7 to 8 kg N required for each 100 kg seed yield. The required N level for production of the crop is met with a combination of: (i) N resident in the soil profile, (ii) N from mineralization, and (iii) applied N, including N applied in spring. Nevertheless, the

applicability of these N application guidelines for the wet climate of western Oregon is unknown.

Application of N in the fall is not a universal practice in winter canola. In Germany, fall N applications in winter oilseed rape are often skipped because the seed yield response to this practice is often low and the amount of N supplied through mineralization can be high at that time (Rathke et al., 2006). But in the winter-wet environment of western Oregon, a fall application of N (made prior to or shortly after planting) has been recommended for winter brassica crops including canola (Ehrensing, 2008). Conley et al. (2004) found that winter canola seed yield was increased by fall applications of 56 kg N ha^{-1} in the Great Plains, USA. Nitrogen increased branching in oilseed rape (Asare and Scarisbrick, 1995; Wang et al., 2014).

Nitrogen uptake in winter canola increases rapidly in early March and then peaks later in April (Wysocki et al., 2007). Nevertheless, timing of spring N application should be based on growth stage rather than calendar date. As a consequence, spring N needs to be applied prior to stem elongation (rosette stage, BBCH 30) in order to be taken up by the plant to support development of the elongating stems and crop canopy, and ultimately seed production. Another reason for the early application is that the crop takes up the N so early in the late winter/early spring period that soil mineralization activity is low at this time and cannot supply the N needs of the plant (Rathke et al., 2006).

Protein content of the seed is an indicator of the N nutrition of the canola plant because N is a key component of the amino acids that form the protein. The source of that N in the seed either is directly distributed from available soil N at the time of seed development or is partitioned (remobilization) from N stores present in above-ground

vegetative tissues during this period. Nearly 25% of all of the N taken up by canola is partitioned to the flowers and developing seed while 87% of the N remobilized from other tissues in the plant ends up in the flowers and seed (Brunel-Muguet et al., 2013).

Nitrogen use efficiency (NUE) is a measure of the effectiveness of N in making contributions to plant productivity (Rathke et al., 2006). Various definitions of this measure have been proposed and have been utilized in studies on canola and other crops. For the purposes of this study, NUE is defined as the ratio of seed yield to total N (pre-plant available N in the soil + applied N). Reported values for NUE in spring canola range from 12 to 27 kg seed kg N^{-1} depending on the rate of N application (Hocking et al., 1997; Svečnjak and Rengel, 2006b; Wang et al., 2014).

The canola crop canopy collapses and falls to the ground when the stems can no longer support the weight of the developing inflorescence and seed in spring. This phenomenon is known as lodging. Plants are most susceptible to lodging when available soil water levels are high and are accompanied by high levels of nitrogen (Islam and Evans, 1994; Conley et al., 2004). Windy conditions or heavy rain can induce lodging. Lodging during flowering restricts pollination and reduces fertilization. Lodging reduced seed yield in oilseed rape by 16% compared to an artificially-supported crop (Islam and Evans, 1994). In addition to reducing seed yield in oilseed rape, lodging reduced stand density, siliques m^{-2}, seeds silique^{-1}, seed weight, above-ground biomass, and HI. Lodging likely reduced light interception throughout the canopy and contributed to lower seed yields in lodged stands (Trethewey, 2009). Self-shading resulting from lodging in canola would likely alter the pattern of N uptake by the plant and remobilization of N reserves to the seed (Brunel-Muguet et al., 2013).

Trinexapac-ethyl plant growth regulator and fungicides reduced seed yield and oil quality losses in winter rapeseed resulting from lodging and disease pressure in Germany (Ijaz and Hornermeier, 2012).

Chapter 2. Spring Nitrogen and Cultivar Effects on Seed and Oil Production Characteristics in Winter Canola (*Brassica napus* L.).

Abstract

Limited information is available on the effects of applied spring nitrogen and cultivar on winter canola (*Brassica napus* L.) seed yield in high-rainfall environments. The objective of this study was to investigate spring-applied N effects on four cultivars of winter canola: Athena, Baldur, Virginia and Kronos. Field trials were conducted over a three-year period at Corvallis, Oregon with four spring N application rates: 0, 56, 112, and 156 kg N ha^{-1}. Lodging severity determined seed yield responses to spring-applied N. Under low or moderate lodging severity, seed yield was increased in proportion to spring N rate. When lodging was severe, seed yields were reduced by application of 168 kg N ha^{-1}. Seed yield increases attributable to spring N ranged up to 75%, while losses under lodged conditions ranged up to 11%. Seed number m^{-2} was the main contributor to increased or decreased yields observed in response to spring N. Seed oil content was largely reduced by increased N rate, but seed protein was unaffected. Oil yield was increased by spring applied N with low or moderate lodging but not with severe lodging. Seed yield and seed weight varied significantly among cultivars in each of the three years. Athena, Baldur, and Virginia averaged 2800 kg ha^{-1} with a different cultivar producing the highest average yield each year, while Kronos consistently yielded the lowest at 2550 kg ha^{-1}. Expression of seed yield by cultivars was governed by a combination of seed number and seed weight. The best spring N rate for winter canola in this study was 112 kg N ha^{-1} because it provided high potential seed yield while minimizing the loss in yield associated with lodging.

Abbreviations: BBCH, Biologische Bundesanstalt, Bundessortenamt und CHemische

Industrie: NUE, nitrogen use efficiency

Keywords: seed yield, lodging, seed weight, oil content, protein content

2.1. Introduction

Canola (*Brassica napus* L.) is one of the world's most important oil seed crops, ranking behind only soybean [*Glycine max* (L.) Merr.] in oil production. Since its development in 1974, canola has grown to account for 10-15% of the world-wide oil crop produced (Ash, 2012). Canola and other edible rapeseed oil production totaled over 23.6 million Mg in 2013 (FAO 2014). Total world-wide seed production of canola and edible rapeseed in 2013 was 65.1 million Mg and the crop was grown on 34 million hectares. Increases in global demand for edible oil products, biofuels, and other specialty applications have continued to spur demand for high-yielding oil seed crops like canola. Preliminary field trials identified the potential of winter canola as a high-yielding rotation crop for the grass seed crop dominated cropping systems of western Oregon (Chastain et al., 2006).

Western Oregon's climate is classified as a Mediterranean warm summer type (Csb) and is marked by mild, wet winters with dry summers (Peel et al., 2007). Annual precipitation in the region is 1015 mm, with 90% recorded between October and April and very little precipitation in late spring and early summer (Taylor, 1993). Winter canola cultivars are bred to take advantage of longer growing seasons in regions with mild winter climates such as the Pacific Northwest USA (Shafii et al., 1992). Spring canola cropping is well-suited for regions with cold winters such as the Northern Great Plains of North America because conditions are too harsh, resulting in poor plant survival. (Johnston et al., 2002). Winter canola crops in the Pacific Northwest can yield more than twice that of spring canola (Ehrensing, 2008).

Current N application recommendations for winter canola production in Oregon have been based on trials conducted in the semi-arid eastern portion of the state (Wysocki et al., 2007). These trials revealed that the total requirement for N by the canola crop is 6.5-7.5 kg ha^{-1} per each 100 kg ha^{-1} in expected seed yield. The required N level for production of the crop is met with a combination of: (i) N resident in the soil profile, (ii) N from mineralization, and (iii) applied N, including N applied in spring. Applicability of these N application guidelines for the wet climate of western Oregon is unknown as no studies have been conducted on winter canola in the region.

Most previous N management studies in winter canola and other winter oilseed rape crops has been done in locales such as Germany (Rathke et al., 2005) and Illinois USA (Bullock and Sawyer, 1991) that receive approximately 40% less annual precipitation than is typical for western Oregon and do not have seasonally concentrated rainfall in the winter months. The mild winter temperatures of the region is beneficial for the over-winter survival of winter canola but high precipitation during the winter and early spring months might be detrimental to timely management of the crop.

The objectives of this study were to: (i) determine the effect of spring nitrogen application on winter canola seed and oil production characteristics in the seasonally wet environment of western Oregon, (ii) ascertain differences among winter canola cultivars for seed and oil production, and (iii) identify best spring nitrogen management practices and winter canola cultivars for the region.

2.2. Materials and Methods

2.2.1. Overview

Field trials were conducted during three crop years (2007-08, 2008-09 and 2009-10) at Oregon State University's Hyslop Crop Science Research Farm (44° 40' N, 123° 11' 36"W) near Corvallis, Oregon, to characterize the effects of spring nitrogen and cultivar on seed and oil production characteristics in winter canola. The soil at the site is a Woodburn silt loam (fine-silty, mixed, superactive, mesic, Aquultic Argixeroll).   The soil was sampled to a depth of 0.6 m for total available N prior to planting each year. The pre-plant available N was 77, 75, and 110 kg N ha^{-1} in 2007, 2008, and 2009, respectively.   Soil pH ranged from 5.7 to 6.1 during the trials, typical for crop production in the region.

The experimental design was a randomized complete block with a split-plot arrangement of treatments and four replications. This design was used to test spring N, cultivars, and potential interactions of these factors. The main plots were spring nitrogen application rates and cultivars were the subplots. Main plots (11.6 m x 17.1 m) were spring-applied N and subplots (4.3 m x 11.6 m) were cultivars.

A fine soil seed bed conducive to winter canola establishment was prepared at the experimental site each year according to the methodology described by Ehrensing (2008). Trifluralin (α,α,α-trifluoro-2,6-dinitro-N,N-dipropyl-p-toluidine) was applied at 5.6 kg ha^{-1} three weeks before planting to control weeds during establishment and early canopy development. A pre-plant application of 56 kg N ha^{-1} and 44 kg S ha^{-1} (16-20-0-13) was made uniformly to all plots during seedbed preparation.

Four winter canola cultivars were chosen for the field trials: Athena, Baldur, Kronos and Virginia. Athena and Virginia are both open-pollinated cultivars (Brown et al., 2005) while Baldur and Kronos are hybrids. Athena and Baldur were the most widely grown winter canola cultivars in eastern Oregon at the time of this study. All cultivars selected were developed via traditional plant breeding techniques and not genetically modified. Winter canola seed was sown by using a double-disc drill at 9 kg seed ha^{-1} in a 15 cm row spacing in mid-September 2007, 2008, and 2009. The seeding rate was not adjusted for seed size among the cultivars. However, stand establishment among all cultivars was adequate for optimum crop yield.

Development stages of the winter canola seed crops in relation to management practices and experimental treatments were characterized by using the BBCH scale (Lancashire et al., 1991). Stands were monitored from crop emergence through establishment, canopy closure and the cessation of growth in winter. Monitoring of crop development resumed with warming temperatures in late February and continued through initiation of stem elongation (BBCH 30).

Spring nitrogen was broadcast as granular urea (46-0-0) in late February 2008, 2009, and 2010 using a tractor-mounted Gandy orbit-air fertilizer spreader. The fertilizer applications dates coincided with the rosette stage but prior to stem elongation (BBCH 30). Application rates were 0, 56, 112, and 168 kg N ha^{-1}. Boron was also applied as a foliar spray of sodium borate in February of each year at a rate of 1.96 kg B ha^{-1} to ensure adequate availability during seed development. Athena and Baldur plots were sampled in 2009 to measure the residual available soil N present in the profile following seed

harvest. Samples were taken from four soil depth increments: 0-15, 15-30, 30-45, and 45-60 cm.

Lodging and the incidence and severity of diseases were monitored. Lodging ratings were conducted on June 20 of each year (about BBCH 77). No lodging was observed 2008. The severity of lodging was assessed in each plot by using a 0 to 9 scale, where 0 = not lodged (fully upright) and 9 = most severely lodged (horizontal).

2.2.2. Seed and Oil Production Characteristics

Seed harvest was conducted in a two-step process (swathing, followed by combining). Plots were harvested in late June of each year by swathing with a small-plot swather at BBCH 85 when 50% of siliques were ripe and seeds were black and hard (Lancashire et al., 1991). Dried windrows were threshed in the field with a plot combine when siliques were brittle enough to be threshed, about two weeks later. Harvested seed from each plot was weighed in the field for a determination of seed dirt weight (weight of the harvested crop prior to seed cleaning), and two subsamples were collected for laboratory analysis. Seed was cleaned by using an M-2B air-screen cleaner (A.T. Farrell, Saginaw, MI) prior to final clean seed yield determination.

Samples to determine seed weight and seed number m^{-2} were hand cleaned using screens and a blower prior to counting. Two 1,000 seed samples from each plot were counted by an electric seed counter (The Old Mill Company, Savage, MD) and weighed. Seed number m^{-2} was calculated for each plot by dividing the clean seed yield harvested from that plot by the individual seed weight. Total nitrogen content of clean and prepared subsamples was determined by the Dumas combustion method using an automated LECO CNS analyzer. Seed protein content was calculated by multiplying the

seed N content by 6.25. Nitrogen use efficiency was calculated by dividing clean seed yield by total N (pre-plant available N + applied N) (Rathke et al., 2006).

Oil content in harvested seed was measured for all treatments by pulsed nuclear magnetic resonance spectroscopy (Krygsman et al., 2004). Oil yield was calculated as the product of clean seed yield and the fractional seed oil content.

2.2.3. Statistical Analysis

Analysis of variance was conducted to test spring N and cultivar main effects and interactions by using the Statistix 8 Analytical Software (Analytical Software, 2003). Bartlett's χ^2 tests revealed that error variances were not homogenous across years; therefore, each year's results were analyzed separately. Treatment means were separated by Fisher's protected LSD values at the 5% level of significance. Regression analyses were conducted to elucidate the nature of relationships between spring N application rates and seed yield.

2.3. Results and Discussion

2.3.1. Crop Growth and Lodging Environment

During seed germination and throughout stand establishment, temperatures and monthly precipitation were generally near the long-term average in all three years (Fig. 2.1). In each year, all cultivars had developed rosettes by November and persisted through colder than average temperatures in both December 2008 and 2009. Temperatures during the post-N application period, starting in late February (BBCH 30), were typical for the region.

Autumn precipitation was adequate for stand establishment of all cultivars even in drier than normal conditions of fall 2008 (Fig. 2.1). Precipitation observed from early spring through seed harvest contrasted sharply among the three years and was marked by below normal rainfall in 2008 (80% of normal), near normal in 2009 (97% of normal), and very wet conditions in 2010 (159% of normal). Over the three years, rainfall variation was most extreme in May during raceme development and flowering (BBCH 50-69). Only 19% of normal rainfall was recorded in May 2008 while in May 2009 and 2010, more than 180% of the normal rainfall was observed. Heavy May rainfall in 2009 and 2010 coincided with lodging events. Weymann et al. (2015) found that 40% of the variability in winter oilseed rape seed yield in Germany was attributable to weather conditions during raceme development and flowering (BBCH 50-65) and later during silique and seed development (BBCH 71-79).

2.3.2. Spring Nitrogen Effects

The analysis of variance revealed that lodging, seed yield, NUE, and oil yield were consistently affected by spring N in all three crop years (Table 2.1). Spring N and

heavy rains caused lodging in 2009 and 2010. Severity of lodging increased in proportion to the rate of N applied (Table 2.2). Increased incidence and severity of lodging in response to N application in canola and oilseed rape has been observed in other studies (Islam and Evans, 1994; Conley at al., 2004). Severity of lodging varied across treatments low to severe in 2009 and from low to moderate in 2010. Lodging severity did not change after the initial observation; once down, plants did not spring back up. Extremely dry conditions during development of the racemes resulted in an absence of lodging in 2008.

A linear relationship between seed yield and spring N was observed in all three crop years although this response varied among years ranging from increased to decreased seed yields (Fig. 2.2). Seed yield was incrementally increased in proportion to spring N rate in 2008 and 2010. Increased seed yields attributable to spring N ranged from 9% with 56 kg N ha^{-1} in 2008 to 75% with 168 kg N ha^{-1} in 2010. The 168 kg N ha^{-1} rate in 2010 produced 8 kg seed ha^{-1} for every additional kg of applied N. These positive responses to applied N in 2008 and 2010 were similar to those observed in other investigations on canola and oilseed rape (Hocking et al., 1997; Jackson, 2000; Rathke et al., 2005).

In contrast to the 2008 and 2010 results, seed yield of winter canola fertilized with 168 kg N ha^{-1} was reduced by 11% compared to the control in 2009 (Fig 2.2). The lack of a positive seed yield response to applied spring N in 2009 and the severity of lodging at high N rates (Table 2.2) suggests that lodging played an important role in the seed yields observed in 2009. In 2009, lodging severity increased with spring N rate with plants in plots treated with 168 kg N ha^{-1} lying nearly horizontal more than a month

before swathing. Lodging reduced seed yield in winter oilseed rape by 16% compared to an artificially-supported crop (Islam and Evans, 1994).   Lodging likely reduced light interception throughout the canopy and contributed to lower seed yields in lodged stands (Trethewey, 2009).

Seed weight was not affected by spring N in 2008 and in 2009 whereas in 2010 the 168 kg N ha^{-1} rate reduced seed weight (Table 2.2). In contrast, Asare and Scarisbrick (1995) reported that N applications increased seed weight in winter oilseed rape. Lodging reduced seed weight in winter oilseed rape (Islam and Evans, 1994), and was likely the cause of the reduction in seed weight in 2010.

Seeds m^{-2} was increased with spring N in 2008 and 2010 with greatest increases in seeds m^{-2} found with spring N rates $\geq$ 112 kg N ha^{-1}. The 168 kg N ha^{-1} rate reduced seeds m^{-2} in 2009, presumably as a result of severe lodging in this treatment. Nevertheless, there was a strong relationship between seeds m^{-2} and seed yield evident for winter canola in this study (Fig. 2.3.). Winter canola seed yield was mostly affected by seed number m^{-2} rather than seed weight. Similar results were found in oilseed rape by Wang et al. (2014). Wright et al. (1995) reported that 99% of the variation in seed yield of canola grown in Australia was accounted for by seed number m^{-2} since individual seed weight did not vary appreciable.

Seed oil content was reduced in proportion to increased spring N rate in 2008, and at spring N rates $\geq$ 112 kg N ha^{-1} in 2010 (Table 2.2.). The oil content of seed was not affected by spring N in 2009. Several reports indicate that seed oil content in oilseed rape or canola was inversely affected by the rate of N (Asare and Scarisbrick, 1995;

Rathke et al., 2006; Jackson, 2000), but Hocking et al., (1997) found that this effect of N on oil content was not always consistent similar to the 2009 results in this trial.

Seed protein content ranged from 169 g kg^{-1} to 176 g kg^{-1} and was not affected by spring N application at any time during the trials. This result is in contrast with other investigations in winter oilseed rape or canola that showed increases in seed protein in response to N applications (Asare and Scarisbrick, 1995; Kutcher et al., 2005). Moreover, seed protein content for winter canola in this study was on the low end of the range of values reported for canola production around the world.

Oil yield was increased by spring N rates ≥ 112 kg N ha^{-1} in 2008 and was increased by all spring N rates in 2010. Spring N reduced oil yield with the 168 kg N ha^{-1} rate in 2009. Similar results for oil yield responses to N application in canola have been previously noted (Hocking et al., 1997; Jackson, 2000). Since seed oil content was inversely related to the rate of spring N application, oil yield was increased with spring N but exhibited a lower magnitude of increase as that observed for seed yield.

2.3.3. Cultivar Effects

Cultivar effects were present in all years for lodging, seed yield, seed weight, seed number, oil content, NUE, and oil yield (Table 2.1). Inconsistent effects of cultivar on lodging severity were noted among years as Baldur and Kronos had the greatest lodging severity in 2009, but Baldur had greater lodging than other cultivars in 2010 (Table 2.3).

Seed yield was influenced by cultivar in all three years but a different cultivar produced the highest seed yield in each year (Fig. 2.4). Among hybrid cultivars, Baldur yielded more than Kronos in 2008 and 2009, but yields were similar in 2010. Across years, Kronos produced the lowest seed yields among cultivars and the two open-

pollinated cultivars (Athena and Virginia) produced the best seed yields. Hybrids typically have greater seed yield (+7%) than open-pollinated cultivars (Rathke et al., 2006), but that result was not evident in this study. An interaction of spring N and cultivar was observed for seed yield in 2010 (Table 2.1). Seed yield of Baldur, Virginia, and Kronos increased in response to each incremental increase in N rate; however, seed yield of Athena did not increase from 0 kg N ha^{-1} to 56 kg N ha^{-1} (data not shown).

The expression of seed yield by cultivars was governed by a combination of seed number and seed weight. Seed weight differed among cultivars in all three years (Table 2.3). Athena consistently produced the greatest seed weight among cultivars averaging 4.81 mg seed^{-1}. The seed weight produced by other cultivars varied among years, but were always lower in weight than Athena. Athena generally produced fewer seeds m^{-2} compared to other cultivars but had the highest seed weight (Table 2.3). Compensation for low seed weight in winter oilseed rape is often accomplished via increased seed number and therefore only a weak correlation has been shown to exist between seed weight and seed yield (Diepenbrock et al., 2000).

Athena and Baldur tended to have higher seed oil content than Virginia and Kronos (Table 2.3). Oil concentration in the seed has been reported to vary among cultivars of winter canola (Shafii et al., 1992). Seed protein content did not differ among cultivars in 2009 and 2010, but Kronos had lower seed protein content in 2008 than Baldur and Virginia. Differences in oil yields were evident among the four cultivars in all years, but Kronos produced the poorest oil yield across years. A single interaction of spring N and cultivar was found in 2010 and the underlying cause for this result was the

lack of seed yield response to 56 kg N ha^{-1} by Athena that was noted earlier. This was considered to be a spurious result.

One consideration in the choice of winter canola cultivars is the consistency of oil yield across seed production environments. None of the cultivars evaluated were free from year to year variability in seed yield or oil content, but Athena, Baldur and Virginia had better overall oil yields than Kronos.

2.3.4. Nitrogen Use Efficiency and N Requirement

An interaction of spring N and cultivar was evident in NUE in 2008 and in 2010, but not in 2009 (Table 2.1). The 0 kg N ha^{-1} rate had the greatest NUE and there was a general decline in NUE with increasing spring N rate in 2008 and 2009 but not in 2010 (Fig. 2.5). Poor NUE values were present across N application rates in 2010. One possible contributing factor to the low NUE values in 2010 was the high pre-plant N present (110 kg N ha^{-1}) in the soil prior to seeding in 2009. In other words, there was a lot of N available to the crop both pre-plant and in subsequent applications but the crop yield response to the N was not strong. Among cultivars in 2008, Kronos had lower NUE at 56 kg N ha^{-1} and 112 kg N ha^{-1} compared to the other cultivars but showed no differences at the other two N rates.

The observed values for NUE in winter canola under the wet conditions of western Oregon ranged from 7.3 to 23.3 kg seed kg N^{-1}. At the same research site in western Oregon and during the same three years as this study, NUE values for camelina (*Camelina sativa* L. Crantz), another *Brassicaceae* family oil seed crop, ranged from 8.7 to 27.3 kg seed kg N^{-1} (Wysocki et al., 2013). Reported values for NUE in canola range

from 12 to 27 kg seed kg N^{-1} depending on the rate of N application (Hocking et al., 1997; Svečnjak and Rengel, 2006b; Wang et al., 2014).

Soil samples taken after seed harvest in 2009 revealed that winter canola efficiently used the spring N applied in 56 and 112 kg N ha^{-1} rates because the total N remaining in the soil across depths was not different from the 0 kg N ha^{-1} control (Fig. 2.6). There was more than double the amount of N resident in the 0-15 cm segment of the soil profile where 168 kg N ha^{-1} had been applied than for the 56 and 112 kg N ha^{-1} rates. Elevated levels of available N were also present following the 168 kg N ha^{-1} rate in the 15-30 and 30-45 cm segments of the soil profile. The 168 kg N ha^{-1} rate was not different from the other spring N rates or the untreated control in the deepest segment of the profile sampled. This result suggests that either the roots were concentrated deeper in the profile and were able to efficiently take the entire N that was applied or that the surface applied N did not make it past the roots to this depth. About 40% of the applied N remains in the crop residue after harvest in spring canola (Jackson, 2000).

From the results of this investigation, the total N requirement for winter canola under western Oregon conditions range from 6.1 and 10.9 kg N per 100 kg seed yield ha^{-1} across years, spring N application rates and cultivars. The extremes of the range of values reported here represent the 0 kg N ha^{-1} (control) on the low end and by lodged crops (high N input with low seed yield) on the high end. The total N requirements for canola as reported by Wysocki et al. (2007) for eastern Oregon fall in the middle of this range (6.5 to 7.5 kg N ha^{-1} per 100 kg yield) and are not appreciably different for western Oregon. Jackson (2000) found that the total N requirement for spring canola in Montana, USA was about 200 kg N ha^{-1} or about 7 to 8 kg N required for each 100 kg seed yield.

Lodging is one of the potential impediments to growing winter canola in a winter-wet environment accompanied by high spring N application rates. Plant growth regulators such as trinexapac-ethyl are employed as lodging control agents to maximize seed yield potential of cool-season grass seed crops in the wet climate of western Oregon (Chastain et al., 2014; Chastain et al., 2015). Similarly, plant growth regulators might be needed to attain a greater proportion of canola seed yield potential in the region's wet climate. Trinexapac-ethyl and fungicides reduced seed yield and oil quality losses in winter rapeseed resulting from lodging and disease pressure (Ijaz and Hornermeier, 2012).

2.4. Conclusions

Winter canola responded to spring N applications with increased seed and oil yields in the wet environment of western Oregon except under conditions of elevated lodging severity. While high N rates resulted in the highest potential seed yields they also produced the greatest risk of lodging and losses in seed yield. Consequently, spring N should be applied at 112 kg N ha^{-1} for winter canola production in western Oregon because this rate best provided high potential seed and oil yield and while minimizing seed and oil yield losses associated with lodging. Seed number m^{-2} was the most influential factor in determining seed yield in winter canola so management practices should be aimed at improving this value. Seed oil content was high but was inversely related to the rate of spring N application, and therefore had a dampening effect on oil yield responses to spring N. Seed protein content was low but was otherwise not affected by spring N. Plant growth regulator applications might be needed to ensure consistent high seed and oil yields of winter canola in the wet environment of western Oregon.

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Table 2.1. Analysis of variance for spring nitrogen (N) and cultivar (C) effects on seed and oil production characteristics in winter canola.

Source of variation	Lodging	Seed yield	Seed weight	Seed number	Oil content	Seed protein	NUE	Oil yield
2008								
N	--	***	ns	*	***	ns	***	*
C	--	***	***	*	***	*	***	***
N x C	--	ns	ns	ns	ns	ns	*	ns
2009								
N	***	*	ns	*	ns	ns	***	*
C	***	*	***	**	***	ns	*	**
N x C	ns†	ns	ns	ns	ns	ns	ns	ns
2010								
N	**	***	*	**	***	ns	*	***
C	***	***	***	*	**	ns	**	***
N x C	Ns	*	ns	ns	ns	ns	**	*

$*P \leq 0.05.$

$**P \leq 0.01.$

$***P \leq 0.001.$

†Not significant.

Table 2.2. Spring-applied nitrogen effects on seed and oil production characteristics in winter canola. Lodging severity scale: 0 = not lodged – all plants upright, 9 = most severely lodged – no upright plants.

Year	Spring nitrogen	Lodging	Seed weight	Seeds m^{-2}	Oil content	Seed protein	Oil yield
	kg ha^{-1}		mg	no. x 10^4	g kg^{-1}	g kg^{-1}	kg ha^{-1}
2008	0	--	4.22 a	6.71 b	469 a	175 a	1325 b
	56	--	4.21 a	7.34 b	460 b	169 a	1422 ab
	112	--	4.18 a	8.02 a	449 c	174 a	1489 a
	168	--	4.14 a	8.13 a	440 d	171 a	1494 a
2009	0	0.5 c†	4.25 a	6.58 ab	443 a	176 a	1231 a
	56	2.2 bc	4.13 a	6.92 a	427 a	169 a	1210 a
	112	3.2 b	4.30 a	6.04 b	440 a	170 a	1133 ab
	168	7.4 a	4.21 a	5.86 c	431 a	174 a	1056 b
2010	0	0.2 c	4.45 a	3.99 d	472 a	173 a	837 c
	56	0.9 bc	4.38 ab	4.67 c	471 a	176 a	957 b
	112	1.8 b	4.34 ab	6.55 b	462 b	174 a	1304 a
	168	3.3 a	4.26 b	7.34 a	450 c	176 a	1396 a

†Means within years followed by the same letter are not significantly different by Fisher's protected LSD values ($P = 0.05$).

Table 2.3. Cultivar effects on seed and oil production characteristics in winter canola.
Lodging severity scale: 0 = not lodged – all plants upright, 9 = most severely lodged – no
upright plants.

Year	Cultivar	Lodging	Seed weight	Seeds m^{-2}	Oil content	Seed protein	Oil yield
			mg	no. x 10^4	g kg^{-1}	g kg^{-1}	kg ha^{-1}
2008	Athena	--	4.73 a	7.15 b	460 a	172 ab	1549 a
	Baldur	--	4.04 b	8.06 a	459 a	175 a	1494 ab
	Virginia	--	3.95 c	8.07 a	451 b	176 a	1433 b
	Kronos	--	4.05 b	6.93 b	448 c	166 b	1254 c
2009	Athena	3.1 bc†	4.81 a	5.41 c	438 a	169 a	1137 b
	Baldur	3.4 b	3.98 c	7.03 a	442 a	176 a	1235 a
	Virginia	2.9 c	4.12 b	5.59 c	426 b	175 a	1156 b
	Kronos	3.9 a	3.98 c	6.37 b	436 a	169 a	1102 b
2010	Athena	1.2 b	4.90 a	4.81 b	465 ab	173 a	1093 bc
	Baldur	2.3 a	4.17 c	5.88 a	468 a	176 a	1140 ab
	Virginia	1.3 b	4.34 b	5.99 a	463 b	175 a	1199 a
	Kronos	1.4 b	4.01 d	5.87 a	458 c	175 a	1062 c

†Means within years followed by the same letter are not significantly different by
Fisher's protected LSD values ($P = 0.05$).
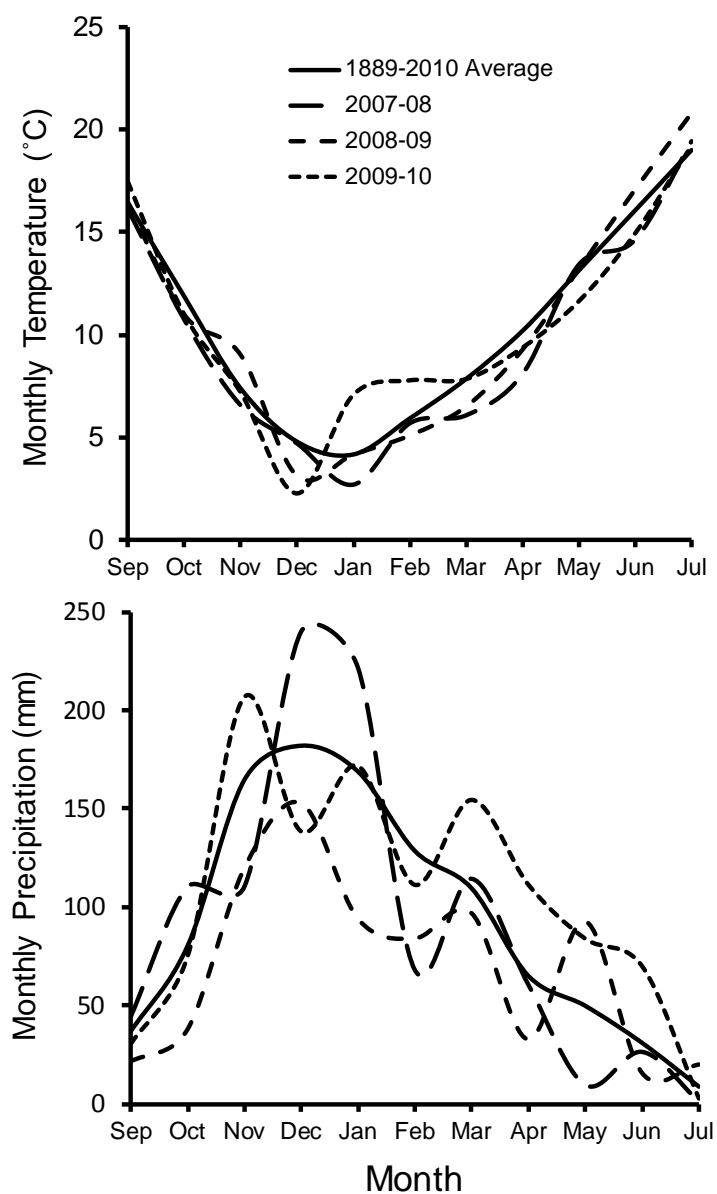
Figure 2.1. Average monthly temperature and precipitation for the 2007-2008, 2008-2009, and 2009-2010 crop years. The long-term mean temperature and precipitation for Corvallis, Oregon is shown as the solid black line.
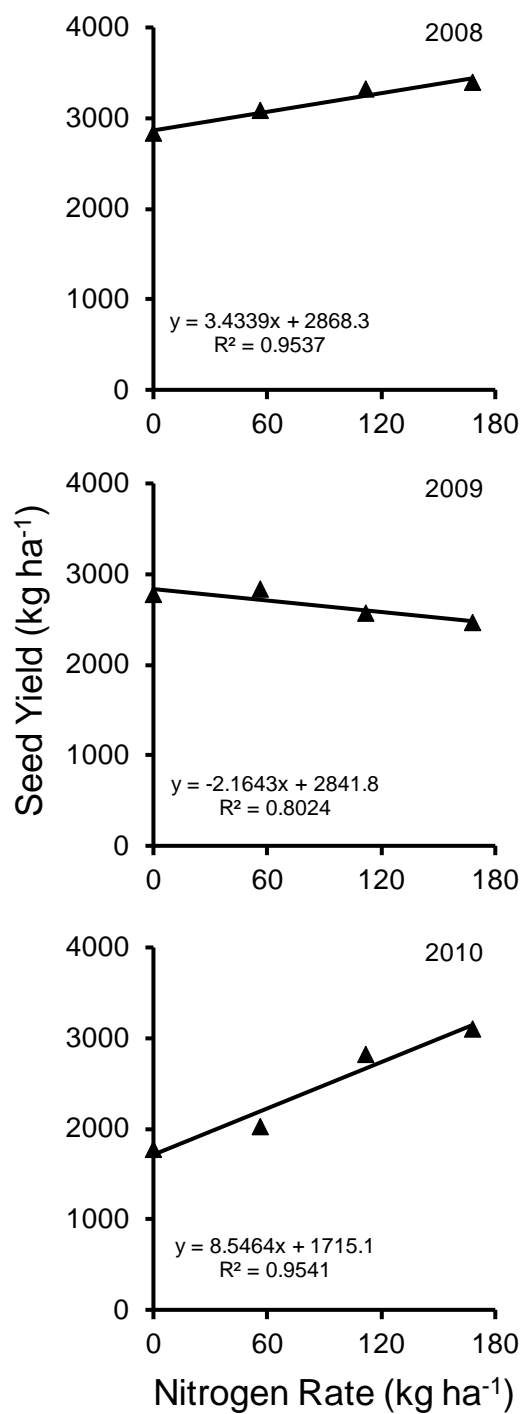
Figure 2.2. Effect of spring-applied nitrogen on seed yield in winter canola. Seed yield values are averaged over four cultivars.
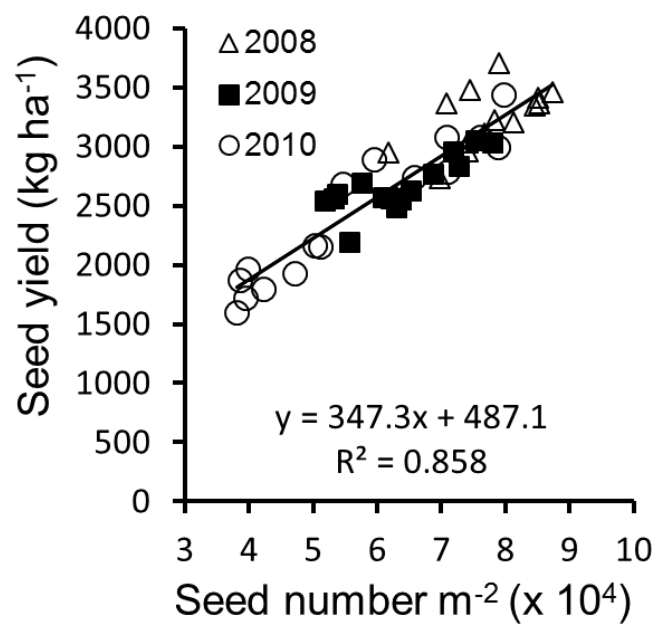
Figure 2.3. Relationship of seed number m[-2] and seed yield in winter canola in three harvest years.
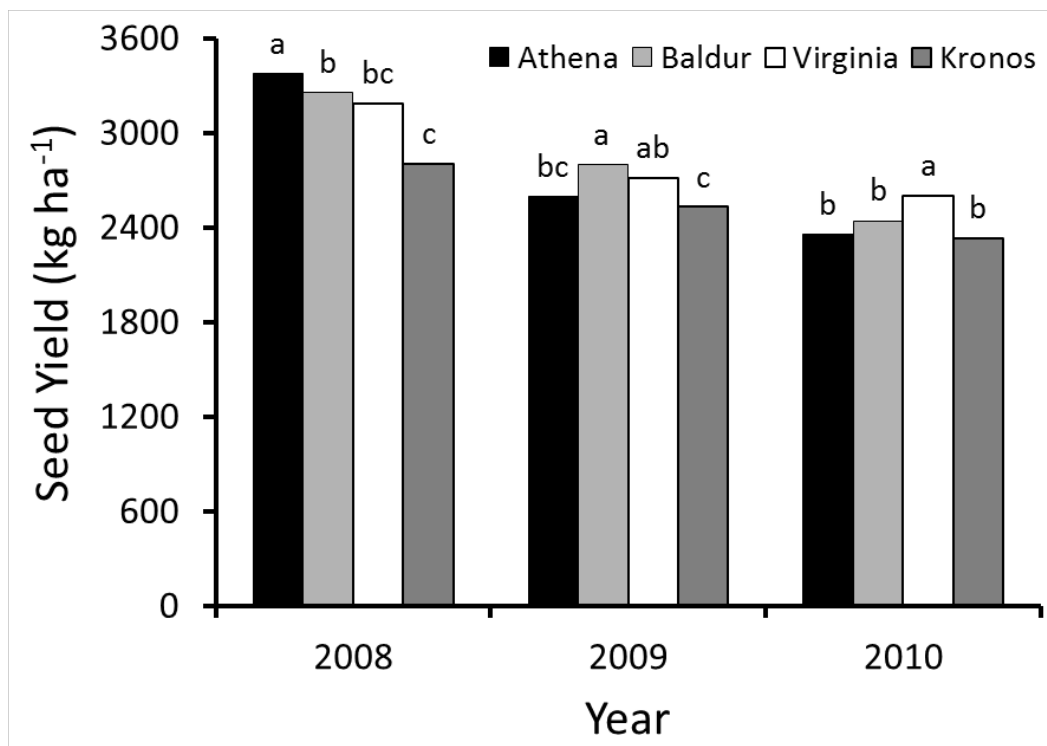
Figure 2.4. Seed yield of winter canola cultivars. Values are averaged across four spring nitrogen application rates. Means within years followed by the same letter are not significantly different by Fisher's protected LSD values ($P = 0.05$).
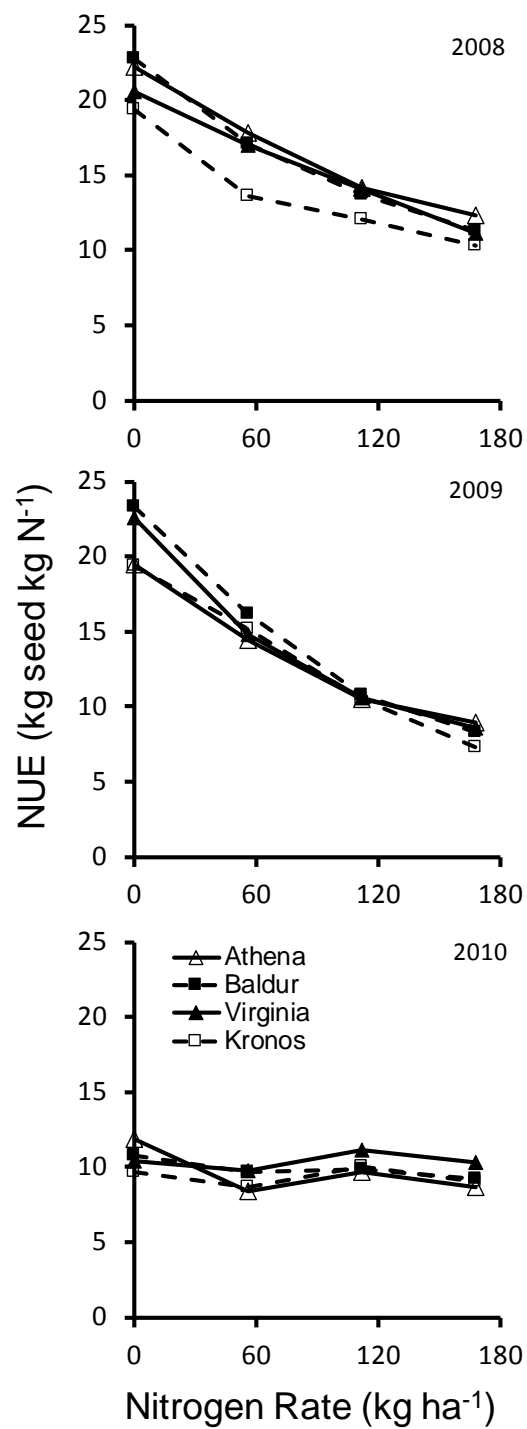
Figure 2.5. Interaction effects of spring-applied nitrogen and cultivar on nitrogen use efficiency (NUE) in winter canola. No interaction was observed in 2009 but was included here for comparison purposes.
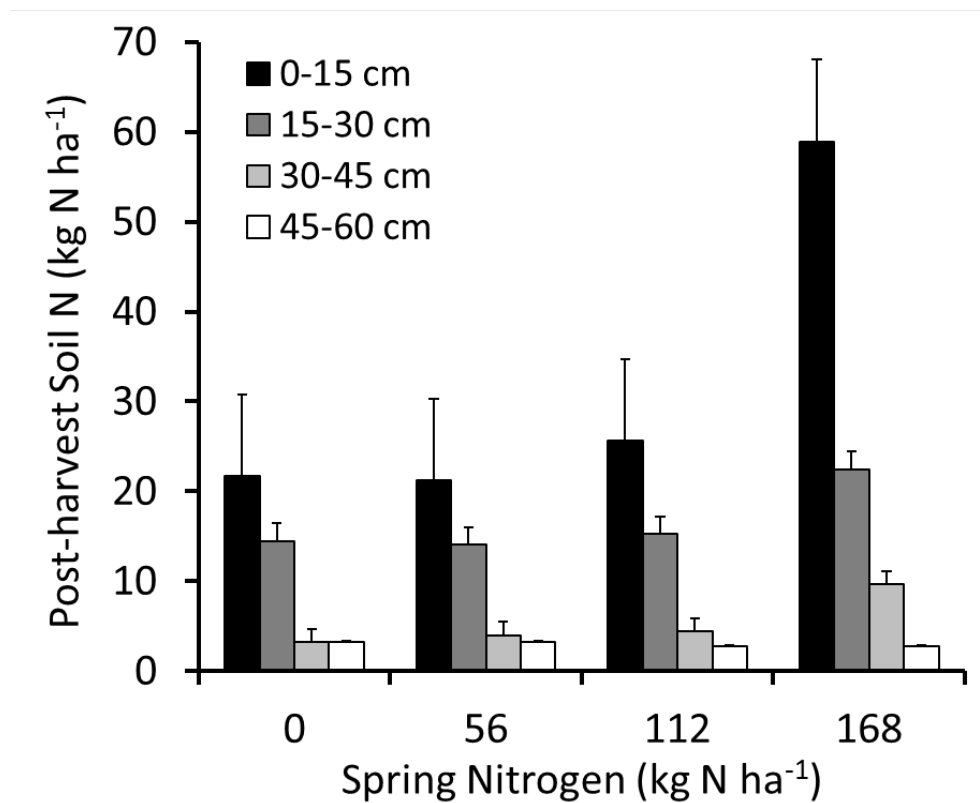
Figure 2.6. Influence of spring N application rate and soil depth on available soil N following winter canola harvest in 2009. Soil was sampled post-harvest in four soil depth increments to 60 cm. Vertical bars represent the standard error of the mean for comparisons among rates within soil depth.

Chapter 3. Spring Nitrogen and Cultivar Effects on Dry Matter Partitioning and Seed Yield Components in Winter Canola (*Brassica napus* L.)

Abstract

Limited information is available on production practices for winter canola (*Brassica napus* L.) in the wet climate of western Oregon, USA. The objective of this study was to investigate spring N rate and cultivar effects on dry matter partitioning and seed yield components. Field trials were conducted at Corvallis Oregon with four spring N rates (0, 56, 112, and 156 kg N ha^{-1}) and two winter canola cultivars (Athena, Baldur) over a three-year period. Dry matter partitioning and expression of seed yield components were differentially affected by lodging. Biomass tended to increase with spring N rate and with advancement in developmental stage except when lodging was severe. Tissue N content was incrementally increased in proportion to the spring N rate. Spring N had no effect on tissue C content except when lodged where C content declined with increasing N rate. Mixed results were observed with HI; spring N rates > 56 kg N ha^{-1} caused reductions in HI in two years but no trend was evident in the third year. Racemes plant^{-1} were not affected by N except when the crop was lodged. Nitrogen rates $\geq$ 112 kg N ha^{-1} increased mainstem siliques raceme^{-1} by 36% in 2008 and by 39% in 2010, but not when lodged in 2009. Seed weight was reduced by N when lodged but otherwise had no effect. Inconsistent cultivar differences were noted for dry matter partitioning and seed yield components. Seed yield components varied in their contributions to seed yield, but mainstem siliques raceme^{-1} produced the most consistent effects on seed yield by increasing seed number m^{-2}. The results of this study improve our understanding of winter canola dry matter and seed yield component responses under management in a wet environment.

Abbreviations: BBCH, Biologische Bundesanstalt, Bundessortenamt und CHemische

Industrie: HI, harvest index

Keywords: stand density, biomass, tissue N content, harvest index, racemes, siliques

3.1. Introduction

Winter canola (*Brassica napus* L.) is a potential rotation crop for the traditional grass seed crop dominated cropping systems of western Oregon. Unfortunately, limited information is available on winter canola production practices for the winter-wet Mediterranean climate in the region. Ferguson et al. (2015a – Chapter 2) found that winter canola seed yield responses to spring N in western Oregon depended on the incidence and severity of lodging. Seed yield was increased by spring N by up to 75% when lodging was absent or low in severity whereas under severe lodging, seed yield losses ranged up to 11% with spring N. The nature of these wide ranging responses in seed yield of winter canola to spring N were needs to be further elucidated.

Nitrogen applications typically result in increased dry matter production (biomass) in canola or oilseed rape (Bullock and Sawyer, 1991; Asare and Scarisbrick, 1995). The partitioning of dry matter to seed yield in relation to this increased biomass is measured by harvest index (HI). A wide range of HI values for canola or oilseed rape have been reported and the effects of N have likewise varied among investigations (Islam and Evans, 1994; Wright et al., 1995; Rathke et al., 2005; Svečnjak and Rengel 2006b).

The seed yield components in winter canola include plants area^{-1} (plant population or stand density), branches plant^{-1}, racemes plant^{-1} (or per branch), siliques raceme^{-1}, seeds silique^{-1}, and individual seed weight. Seed yield is the mathematical product of these components and the individual components can be expressed in several ways. Seed yield components in winter oil rapeseed or canola can be expressed as primary yield components and secondary yield components (Diepenbrock et al., 2000).

Primary yield components are thought to have a direct effect on seed yield and include plants area^{-1}, siliques plant^{-1}, seeds silique^{-1}, and individual seed weight.

Seed yield components vary widely in their impact on seed yield in canola and oilseed rape according to the literature. Several studies show that applied N increased seed yields in canola through greater numbers of siliques plant^{-1} rather than by increased seeds silique^{-1} or seed weight (Asare and Scarisbrick, 1995; Hocking et al., 1997; Svečnjak and Rengel, 2006b). Conversely, Wang et al. (2014) found that seeds silique^{-1} was increased by N application but not seed weight in oilseed rape in China. Nitrogen increased seeds silique^{-1}, and in turn, contributed to greater seeds m^{-2} and ultimately seed yield. Seed yield variation in winter oilseed rape in Germany did not appear to be related to the number of siliques plant^{-1}, seeds silique^{-1}, or the number of branches present on the plant (Ijaz and Hornermeier, 2012).

The objective of this study was to ascertain the influence of spring nitrogen and cultivars on dry matter partitioning and on the expression of seed yield components in winter canola in western Oregon.

3.2. Materials and Methods

3.2.1. Overview

Field trials were conducted during three crop years (2007-08, 2008-09 and 2009-10) at Oregon State University's Hyslop Crop Science Research Farm (44° 40' N, 123° 11' 36"W) near Corvallis, Oregon, to characterize the effects of spring nitrogen and cultivar on dry matter partitioning and seed yield components in winter canola. The soil at the site is a Woodburn silt loam (fine-silty, mixed, superactive, mesic, Aquultic Argixeroll). The experimental design was a randomized complete block with a split-plot arrangement of treatments and four replications. This design was used to test spring N, cultivars, and potential interactions of these factors. The main plots were spring nitrogen application rates and cultivars were the subplots. Main plots (11.6 m x 17.1 m) were spring-applied N and subplots (4.3 m x 11.6 m) were cultivars.

Two non-GM winter canola cultivars (Athena – open pollinated, Baldur - hybrid) were chosen for analysis of dry matter partitioning and seed yield components. Athena and Baldur were the most widely grown winter canola cultivars in the eastern part of Oregon at the time of this study. Development stages of the winter canola seed crops in relation to management practices and experimental treatments were characterized by using the BBCH scale (Lancashire et al., 1991).

The soil was sampled to a depth of 0.6 m for available N (NO_3^- and NH_4^+) prior to planting each year. The pre-plant available N was 77, 75, and 110 kg N ha^{-1} in 2007, 2008, and 2009, respectively. A pre-plant broadcast of 56 kg N ha^{-1} and 44 kg S ha^{-1} as dry ammonium phosphate-sulfate (16-20-0-13) was made uniformly to all plots during seedbed preparation. Spring nitrogen was applied as dry granular urea (46-0-0) in late

February 2008, 2009, and 2010 using a tractor-mounted Gandy orbit-air fertilizer spreader. The fertilizer applications dates coincided with the rosette stage but prior to stem elongation (BBCH 30). Application rates were 0, 56, 112, and 168 kg N ha^{-1}. Additional details of plot management and experimental procedures were described by Ferguson et al. (2015a) – Chapter 2.

3.2.2. Dry Matter Partitioning

Plant stand density was determined on two 0.1 m^2 samples taken at random from each plot at the end of flowering (BBCH 69) and was reported as the average for the samples. Two 0.1 m^2 samples were taken at random at the end of flowering (BBCH 69) in mid-June and again at the time of swathing (BBCH 85) in late June of each of the three years for above-ground biomass determination. Samples were dried at approximately 70° C for 30 hours in on-site dryers. Sample dry weights were recorded and combined to determine above-ground biomass for each plot.

Dried above-ground biomass samples taken at BBCH 69 were further processed for tissue C and N analysis. The samples were chipped with a wood chipper to break down plant stem, leaf and raceme tissues and were reduced in size by dividing. The divided materials were then ground in preparation for tissue analysis. Total carbon (structural and non-structural) and total nitrogen content in prepared above-ground plant tissues were determined by using a LECO CNS combustion analyzer (Jones and Case, 1990). Harvest index was calculated as the ratio of clean seed yield (reported by Ferguson et al., 2015 – Chapter 2) to above-ground biomass at BBCH 85.

3.2.3. Seed Yield Components

The seed yield components measured included racemes plant^{-1}, siliques raceme^{-1}, seeds silique^{-1}, and the weight of individual seeds harvested from each silique. Two 0.1 m^2 samples were taken from each plot at BBCH 84 for the assessment of seed yield components in each of the three years. The samples were dried at approximately 70° C for 25 hours in on-site dryers. The plants in each sample were examined to determine branching patterns and silique location on branches. Each plant possessed one mainstem and varying numbers of primary (1°) and secondary (2°) branches. The number of racemes present on the mainstem and branches were counted and recorded. Since the appearance of tertiary branches was both infrequent and inconsistent, the results from these branches were omitted from the analysis. The number of siliques associated with the mainstem and each order of branching were counted and then removed. Once removed, seeds were extracted from the siliques by hand, counted and then recorded according to location on the plant. The weight of each seeds harvested from each silique was determined.

3.2.4. Statistical Analysis

Analysis of variance was conducted to test spring N and cultivar main effects and interactions by using the Statistix 8 Analytical Software (Analytical Software, 2003). Bartlett's χ^2 tests revealed that error variances were not homogenous across years; therefore, each year's results were analyzed separately. Treatment means were separated by Fisher's protected LSD values at the 5% level of significance. In order to elucidate the nature of relationships between seed yield components and seed yield, regression analyses were conducted. Linear correlation coefficients were calculated for seed yield components and seed yield.

3.3. Results and Discussion

3.3.1. Lodging

Precipitation in May of each crop year had a strong impact on the response of winter canola to spring N application. The month of May is a critical period for seed production in winter canola and the rainfall in this month varied widely among the three years of the study. Rainfall in May 2008 was only 19% of normal while rainfall in May 2009 and 2010, more than 180% of the normal rainfall was recorded. This extreme variation in rainfall resulted in the absence of lodging in 2008 whereas in 2009 and 2010, lodging ranged from low to extreme depending on spring N application rate (Fig. 3.1). Winter canola seed yield increases attributable to spring N ranged upwards to 75% while losses in seed yield under lodged conditions ranged up to 11% (Ferguson et al., 2015a – Chapter 2).

3.3.2. Spring Nitrogen Effects

The effects of spring N on characteristics of dry matter partitioning in winter canola were differentially affected by lodging. Spring N had consistent effects on tissue N and HI across all three years of the study among characteristics of dry matter partitioning; however, spring N influences on seed yield components were inconsistent among years (Table 3.1). Stand density was not affected by spring N in 2008 and 2010 (Table 3.2). In contrast, stand density was reduced by spring N in 2009 with the greatest reduction at the highest N rate. The reduced stands caused by spring N was most likely caused by the moderate to severe lodging observed in 2009. Stand density might have been reduced as a result of widespread stem breakage in the lodged crop (Islam and Evans, 1994).

Above-ground biomass increased from late flowering (BBCH 69) to time of crop swathing (50% of pods ripe and seed black and hard, BBCH 85) in 2008 and 2010 (Table 3.2). However, biomass was reduced from BBCH 69 to BBCH 85 in 2009, another manifestation of the lodging in that year. This reduction in biomass was possibly due to poorer growth or senescence of tissue or both. Islam and Evans (1994) found that lodging reduced biomass of oilseed rape. Spring N had no statistically significant effect on biomass at BBCH 69 in 2008 and 2009, but was increased by N rates $\geq$ 112 kg N ha^{-1} in 2010. Spring N increased biomass at BBCH 85 with rates $\geq$ 112 kg N ha^{-1} in 2008 and by 112 kg N ha^{-1} in 2010, but had no effect on biomass at BBCH 85 in 2009. Similar mixed effects of N on biomass production was noted in spring canola (Kutcher et al., 2005).

Above-ground tissue N content at BBCH 69 (end of flowering) was consistently increased by spring N in all three years (Table 3.2). Significant increases in tissue N content were observed in every year with spring N rate $\geq$ 112 kg N ha^{-1}. Tissue N contents at BBCH 69 ranged from 9.8 g kg^{-1} to 21.1 g kg^{-1} over years and treatments. Bullock and Sawyer (1991) reported that tissue N concentrations at flowering in winter canola in the Midwest USA ranged from 13 g kg^{-1} to 30 g kg^{-1} with N rates in the range used in this study. Hocking et al. (1997) found that at the end of flowering, whole-plant tissue N contents ranged from 11.2 g kg^{-1} (0 kg N ha^{-1}) to 15.2 g kg^{-1} (150 kg N ha^{-1}) in canola. Tissue C content at BBCH 69 was not affected by spring N applications in 2008 and 2010. Spring N caused reductions in tissue C content that were roughly proportional to the increases in tissue N content in 2009.

The elevated tissue N content values with applied spring N clearly indicate that N was taken up by the plant. However, seed protein content in winter canola was not similarly increased by the application of N (Ferguson et al., 2015a – Chapter 2). The possible reason for this disparity between tissue N content and seed protein content was that there was much mutual shading among plants as a result of high plant population density in the winter canola crops grown in this study. Under conditions of mutual shading (and presumably lodging), N is preferentially partitioned by increased mobilization from reserves in plant tissues to the raceme (and seed), thus adequate N supply would have been available in the seed at the time of protein formation thereby eliminating potential differences in protein content among N rates (Brunel-Muguet et al., 2013).

Harvest index provides a measure of how spring N management in winter canola might impact partitioning to seed in relation to total above-ground biomass production. Spring N rates ≥ 112 kg N ha^{-1} reduced HI in 2008 and 2009, the lowest HI values were found in 56 and 112 kg N ha^{-1} rates in 2010 (Table 3.2). High HI in 2009 were likely the result of a greater effect of lodging in reducing biomass at harvest (BBCH 85) than in affecting seed yield. In contrast, Islam and Evans (1994) found that HI was increased in an artificially supported oilseed rape crop over a lodged crop. Values for HI in this study ranged from 0.12 to 0.35 while reported HI values for canola and oilseed rape range from 0.11 to 0.50 (Islam and Evans, 1994; Wright et al., 1995; Rathke et al., 2005; Svečnjak and Rengel 2006b).

Seed yield components in winter canola were differentially affected by spring N over the three years of the study as a result of crop lodging. Spring N had no effect on

racemes plant^{-1} produced on 1°branches and 2° branches in 2008 and 2010, but spring N

increased the number of racemes plant^{-1} produced on 1° branches and 2° branches in

2009 (Table 3.3). These spring N-induced increases in racemes plant^{-1} in 2009 were

likely a compensatory response to the loss in stand density with spring N (Table 3.2).

Each mainstem produced one raceme regardless of spring N rate (data not shown). Total

number of racemes plant^{-1} ranged from 3.3 to 7.1 over years and spring N treatments.

There were more siliques produced on mainstem racemes than on those produced

on 1° branches and 2° branches in all three years (Table 3.3). Similar results were found

in other studies (Trethewey, 2009; Wang et al. 2011). The number of siliques raceme^{-1}

produced by the mainstem was increased by spring N rates ≥ 112 kg N ha^{-1} in 2008 and

2010, but no effects of N were noted for siliques raceme^{-1} produced on 1° branches and

2° branches (Table 3.3). Nitrogen rates ≥ 112 kg N ha^{-1} increased mainstem siliques

raceme^{-1} by 36% in 2008 and 39% in 2010. In contrast, spring N had no effect on

siliques raceme^{-1} produced by the mainstem in 2009, but the number of siliques raceme^{-1}

produced by 1° branches and 2° branches was increased in response to spring N. There is

evidence of compensation in the number of siliques raceme^{-1} on 1° branches and 2°

branches for the lack of increase in mainstem siliques raceme^{-1} in 2009. Both responses

might be the downstream developmental effect of spring N on racemes plant^{-1} (Wang et

al., 2011).

There were no effects of spring N on seeds silique^{-1} in any year (Table 3.4). This

finding is in agreement with other investigations (Asare and Scarisbrick, 1995; Hocking

et al., 1997; Svečnjak and Rengel, 2006b). There were too few seed produced in siliques

on 2° branches to report statistically valid results so that data is not shown here. Spring

N had no influence on the individual seed weight of seed produced on the mainstem or on 1° branches in 2008 (Table 3.4). Seed weight of mainstem-produced seeds was reduced by 168 kg N ha^{-1} in 2009, but no spring N effects were apparent in seed from 1° branches. Spring N $\geq$ 112 kg N ha^{-1} reduced seed weight of seed produced on mainstem and 1° branches in 2010. Seed weight is the last seed yield component to complete development (Diepenbrock, 2000) and develops as dry matter is partitioned at various rates, depending on silique branch position, through approximately 50 days after flowering (Diepenbrock and Geisler, 1979).

3.3.3. Cultivar Effects

Characteristics of dry matter partitioning and seed yield components in winter canola were not consistently influenced by cultivar over years with the exception of seed weight (Table 3.1). Stand density did not differ between cultivars in 2008 and 2010, but Athena produced better stands than Baldur in 2009 (Table 3.5). Baldur produced greater biomass than Athena at BBCH 69 in 2008 but no other cultivar effects on biomass were recorded. Tissue N content was greater in Athena than Baldur in 2008 but the reverse was found for tissue C content. Differences in biomass responses to N was found to not be consistent with differences in tissue N content among spring canola cultivars (Svečnjak and Rengel 2006a). Harvest index was not affected by cultivar except in 2008 where Athena had greater HI than Baldur.

No effects of cultivar were observed with regard to racemes plant^{-1} in 2008 (Table 3.6). Baldur produced more racemes plant^{-1} in both 1° branches and 2° branches than Athena in 2009 and 2010. Greater numbers of siliques raceme^{-1} were present in Baldur than in Athena in 2008 on 2° branches, on the mainstem and 1° branches in 2009, and on

1° branches and 2° branches in 2010. Differences among cultivars for siliques plant^{-1} have been reported in winter oilseed rape (Asare and Scarisbrick, 1995) and in spring canola (Svečnjak and Rengel 2006b).

No differences between cultivars was found in the number of mainstem seeds silique^{-1}, but Baldur produced more seeds silique^{-1} on 1° branches in 2010 (Table 3.7). The weight of Athena seed was consistently greater than Baldur regardless of year, or position of seed formation – mainstem or 1° branches.

There were no spring N x cultivar interactions for stand density or measures of dry matter partitioning (Table 3.1). Spring N x cultivar interactions were found for the following seed yield components: 1° branch siliques raceme^{-1} and mainstem seeds silique^{-1} in 2009, and in 1° branch seeds silique^{-1} in 2010.

3.3.4. Relationship to Seed Yield

Primary seed yield components as defined by Diepenbrock et al. (2000) for the most part did not make significant contributions to winter canola seed yield in this study. Siliques plant^{-1} ($r = 0.351$, $P>0.05$), seeds silique^{-1} ($r = 0.349$, $P>0.05$), and seed weight ($r = -0.144$, $P>0.05$) were primary seed yield components that had no measurable effect on seed yield.   The only primary seed yield component that was influential in determining seed yield was stand density ($r = 0.455$, $P<0.05$).

Seed number m^{-2} ($r = 0.926$, $P<0.01$), a secondary seed yield component, was the most important characteristic in determining winter canola seed yield responses in this study (Ferguson et al., 2015a – Chapter 2). Where does the spring N-induced increases in seed number originate since there were no differences among treatments (N rates) with regard to number of seeds silique^{-1}? Another secondary seed yield component, siliques

raceme^{-1}, made important in contributions to seed number m^{-2} and ultimately, seed yield. The number of siliques raceme^{-1} on the mainstem ($r = 0.547$, $P<0.01$) and on 1° branches ($r = 0.425$, $P<0.05$) were related to seed yield (Fig. 3.2). While seeds silique^{-1} had no direct effect on yield, the presence of more siliques raceme^{-1} on mainstems and 1° branches contributed to greater seeds plant^{-1} ($r = 0.445$, $P<0.05$), and in turn, greater seed number m^{-2}. Seed yield components involved in the flowering process such as the number of racemes plant^{-1} did not affect seed yield ($r = -0.031$, $P>0.05$).

Habekotté (1993) found that both the number of siliques m^{-2} and seeds m^{-2} were related to the size of crop biomass during flowering in oilseed rape. This is a classical source-sink relationship where the source is the biomass (photosynthetic capture system) and the sink is the developing siliques or seeds. Therefore, seed yield in canola is related to the size, architecture, and health of the plant canopy. Several studies indicate that seed yield of canola and oilseed rape is more limited by the source than by the availability of sinks including siliques, ovules, and seeds (Diepenbrock and Geisler, 1979; Habekotté, 1993; Wang et al., 2011; Weymann et al. 2015). To illustrate this source limitation, Wang et al. (2011) found that removal of either mainstem racemes or branch racemes increased the number of ovules silique^{-1}, seeds silique^{-1}, and siliques raceme^{-1} in the remaining racemes. Habekotté (1993) reported that current photosynthesis was more important than partitioning from reserves elsewhere in the plant as this remobilization accounted for at most 12% of seed yield. Disruption of crop canopy architecture by lodging had strong effects on biomass production at a critical time in seed yield development and likely further affected canopy photosynthetic capacity important for partitioning to the ovules and developing seeds.

3.4. Conclusions

Spring N had multiple effects on dry matter partitioning and seed yield components in winter canola although the responses were differentially mediated by the severity of lodging. Tissue N content at the end of flowering was consistently elevated in the above-ground biomass and was an indication of the successful uptake of applied spring N. Biomass was generally increased by N but in this study the results were less consistent as reported by others as a consequence of lodging. Partitioning to seed is important for high seed yield but HI was on the low end of the reported range of values except when lodging was observed. Siliques raceme^{-1} produced by the mainstem raceme was the most important seed yield component measured in the study, and made a major contribution to seed number m^{-2} – the chief determinant of seed yield. Maximum number of siliques raceme^{-1} were produced with the 112 kg N ha^{-1} rate, the same rate recommended for producing high seed yield potential and reducing the risk of lodging losses. The results of this investigation improve our understanding of winter canola dry matter and seed yield component responses under management in the wet environment of western Oregon.

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Table 3.1. Analysis of variance for spring nitrogen (N) and cultivar (C) effects on stand density, dry matter partitioning, and seed yield components in winter canola.

Characteristics	2008			2009			2010		
	N	C	N x C	N	C	N x C	N	C	N x C
Stand density	ns†	ns	ns	***	***	ns	ns	*	ns
Biomass									
BBCH 69	ns	*	ns	ns	ns	ns	*	ns	ns
BBCH 85	*	ns	ns	ns	ns	ns	*	ns	ns
Tissue N	***	*	ns	***	ns	ns	*	ns	ns
Tissue C	ns	*	ns	**	ns	ns	ns	ns	ns
Harvest index	*	*	ns	*	ns	ns	*	ns	ns
Racemes plant^{-1}									
1°branches	ns	ns	ns	**	**	ns	ns	**	ns
2°branches	ns	ns	ns	*	**	ns	ns	**	ns
Siliques raceme^{-1}									
Mainstem	*	ns	ns	ns	***	ns	**	ns	ns
1°branches	ns	ns	ns	**	**	*	ns	***	ns
2°branches	ns	*	ns	*	ns	ns	ns	**	ns
Seeds silique^{-1}									
Mainstem	ns	ns	ns	ns	ns	**	ns	ns	ns
1°branches	ns	ns	ns	ns	ns	ns	ns	**	*
Seed weight									
Mainstem	ns	***	ns	**	***	ns	*	***	ns
1°branches	ns	**	ns	ns	***	ns	*	***	ns

*$P \leq 0.05$.

**$P \leq 0.01$.

***$P \leq 0.001$.

†Not significant.

Table 3.2. Spring nitrogen effects on stand density and dry matter partitioning in winter canola.

Year	Spring nitrogen	Stand density	Biomass		Tissue content		Harvest index
			BBCH 69	BBCH 85	N	C	
	kg ha^{-1}	plants m^{-2}	Mg ha^{-1}	Mg ha^{-1}	g kg^{-1}	g kg^{-1}	
2008	0	153 a†	9.9 a	16.3 b	9.8 c	413 a	0.21 a
	56	140 a	14.7 a	19.2 b	13.6 b	409 a	0.19 a
	112	126 a	15.3 a	26.6 a	15.3 b	410 a	0.13 b
	168	118 a	13.8 a	27.6 a	18.9 a	412 a	0.13 b
2009	0	144 a	10.6 a	8.9 a	13.3 b	415 a	0.32 a
	56	111 b	13.0 a	8.7 a	15.4 b	408 ab	0.35 a
	112	111 b	13.9 a	10.3 a	19.7 a	402 bc	0.26 b
	168	79 c	14.4 a	10.4 a	21.1 a	396 c	0.26 b
2010	0	73 a	9.7 c	14.2 b	10.1 c	393 a	0.14 ab
	56	93 a	11.8 bc	17.9 b	12.2 bc	391 a	0.12 b
	112	108 a	15.3 ab	22.7 a	16.3 ab	381 a	0.12 b
	168	90 a	17.3 a	17.6 b	17.9 a	389 a	0.17 a

†Means within years followed by the same letter are not significantly different by Fisher's protected LSD values ($P = 0.05$).

Table 3.3. Spring nitrogen effects on racemes plant^{-1} and siliques raceme^{-1} in winter canola.

Year	Spring nitrogen	Racemes plant^{-1}		Siliques raceme^{-1}		
		1°branches	2°branches	Mainstem	1°branches	2°branches
	kg ha^{-1}					
2008	0	1.9 a†	0.4 a	32.9 c	9.9 a	1.1 a
	56	2.7 a	0.8 a	37.3 bc	8.7 a	0.8 a
	112	3.8 a	1.0 a	45.0 ab	14.2 a	1.9 a
	168	4.5 a	1.6 a	49.2 a	14.2 a	3.0 a
2009	0	2.5 c	0.0 b	31.9 a	3.5 c	0.0 b
	56	3.3 bc	0.4 ab	36.0 a	6.6 b	0.9 b
	112	4.2 ab	0.8 a	33.4 a	7.8 ab	1.6 ab
	168	5.0 a	0.8 a	35.4 a	10.1 a	2.9 a
2010	0	3.2 a	0.1 a	32.1 b	6.7 a	0.2 a
	56	4.1 a	0.6 a	36.2 b	9.8 a	0.7 a
	112	5.1 a	0.7 a	44.5 a	10.6 a	0.5 a
	168	4.5 a	0.3 a	43.1 a	9.6 a	0.3 a

†Means within years followed by the same letter are not significantly different by Fisher's protected LSD values ($P = 0.05$).

Table 3.4. Spring nitrogen effects on seed silique^{-1} and seed weight in winter canola.

Year	Spring nitrogen	Seeds silique^{-1}		Seed weight	
		Mainstem	1°branches	Mainstem	1°branches
	kg ha^{-1}			----------- mg -----------	
2008	0	16.4 a†	16.4 a	3.33 a	3.06 a
	56	17.0 a	16.3 a	3.31 a	3.31 a
	112	20.3 a	17.8 a	3.14 a	2.94 a
	168	17.5 a	16.9 a	3.29 a	2.98 a
2009	0	18.9 a	16.6 a	4.33 a	4.51 a
	56	17.0 a	16.1 a	4.25 a	4.08 a
	112	18.0 a	17.1 a	4.18 a	4.25 a
	168	16.0 a	15.8 a	3.87 b	4.12 a
2010	0	20.8 a	15.4 a	3.59 a	3.39 a
	56	19.1 a	15.1 a	3.47 ab	3.36 a
	112	20.8 a	15.2 a	3.28 bc	2.96 b
	168	21.2 a	14.7 a	3.23 c	2.99 b

†Means within years followed by the same letter are not significantly different by Fisher's protected LSD values ($P = 0.05$).

Table 3.5. Cultivar effects on stand density and dry matter partitioning in winter canola.

Year	Cultivar	Stand density	Biomass		Tissue content		Harvest index
			BBCH 69	BBCH 85	N	C	
		plants m^{-2}	Mg ha^{-1}	Mg ha^{-1}	g kg^{-1}	g kg^{-1}	
2008	Athena	133 a†	11.7 b	20.5 a	15.2 a	408 b	0.19 a
	Baldur	135 a	15.2 a	24.4 a	13.5 b	414 a	0.14 b
2009	Athena	131 b	11.8 a	9.6 a	18.0 a	405 a	0.29 a
	Baldur	94 a	14.2 a	9.6 a	16.7 a	405 a	0.31 a
2010	Athena	84 a	12.1 a	17.7 a	14.8 a	386 a	0.14 a
	Baldur	97 a	15.0 a	18.5 a	13.4 a	391 a	0.14 a

†Means within years followed by the same letter are not significantly different by Fisher's protected LSD values ($P = 0.05$).

Table 3.6. Cultivar effects on racemes plant^{-1} and siliques raceme^{-1} in winter canola.

| Year | Cultivar | Racemes plant^{-1} | | Siliques raceme^{-1} | | |
		1°branches	2°branches	Mainstem	1°branches	2°branches
2008	Athena	2.9 a†	0.6 a	39.2 a	11.9 a	0.9 b
	Baldur	3.6 a	1.4 a	43.0 a	12.0 a	2.6 a
2009	Athena	3.1 b	0.1 b	29.7 b	5.2 b	0.9 a
	Baldur	4.5 a	0.9 a	39.0 a	8.9 a	1.8 a
2010	Athena	3.7 b	0.0 b	41.3 a	6.6 b	0.0 b
	Baldur	4.7 a	0.8 a	36.6 a	11.7 a	0.7 a

†Means within years followed by the same letter are not significantly different by Fisher's protected LSD values ($P = 0.05$).

Table 3.7. Cultivar effects on seed silique^{-1} and seed weight in winter canola.

Year	Cultivar	Seeds silique^{-1}		Seed weight	
		Mainstem	1°branches	Mainstem	1°branches
				----------- mg -----------	
2008	Athena	17.1 a†	17.6 a	3.51 a	3.26 a
	Baldur	18.6 a	16.0 a	3.03 b	2.89 b
2009	Athena	17.8 a	15.7 a	4.53 a	4.38 a
	Baldur	17.2 a	17.1 a	3.77 b	3.78 b
2010	Athena	19.8 a	14.2 b	3.63 a	3.42 a
	Baldur	21.1 a	16.1 a	3.12 b	2.93 b

†Means within years followed by the same letter are not significantly different by Fisher's protected LSD values ($P = 0.05$).
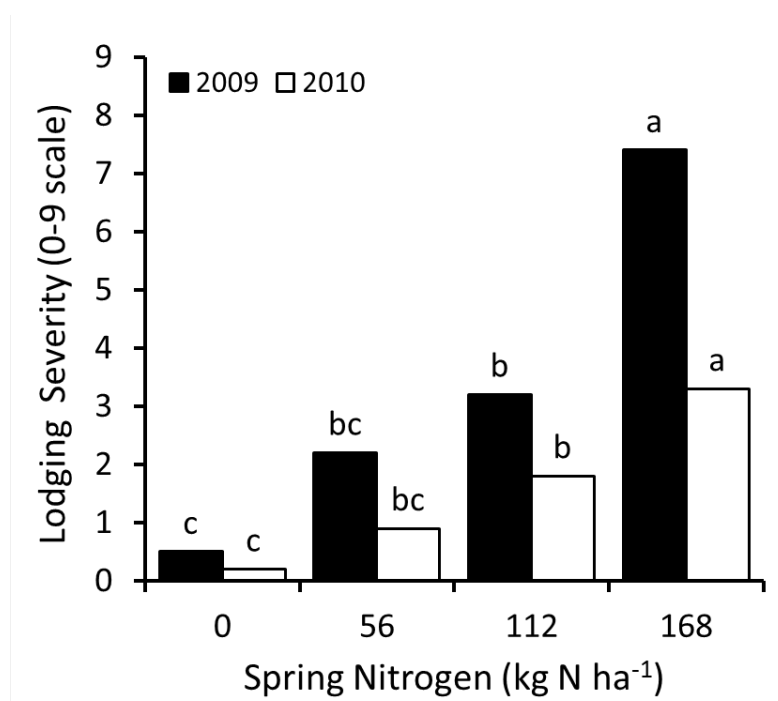
Figure 3.1. Spring nitrogen effects on lodging in winter canola in two years. Lodging severity scale: 0 = not lodged – all plants upright, 9 = most severely lodged – no upright plants. Means within years followed by the same letter are not significantly different by Fisher's protected LSD values ($P = 0.05$).
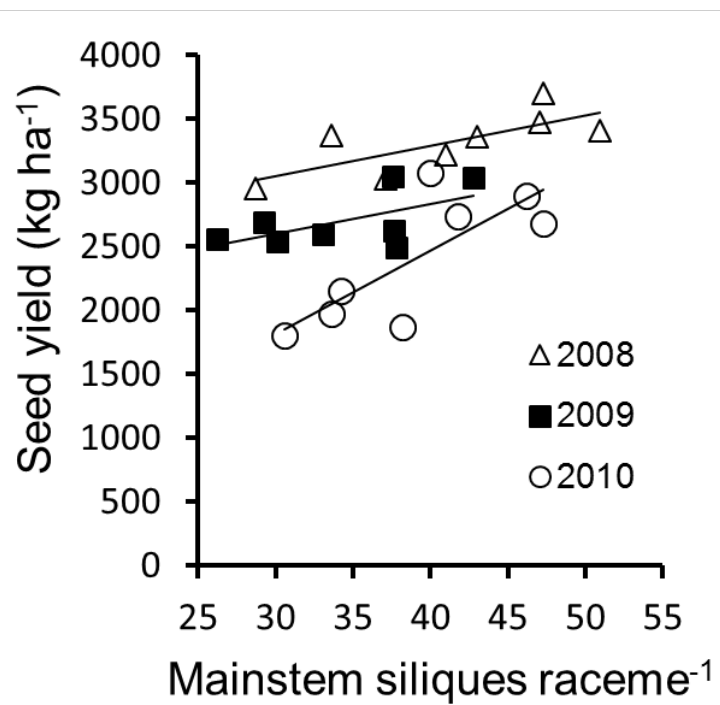
Figure 3.2. Relationship of mainstem siliques raceme[-1] and seed yield in winter canola in three harvest years. Equations for the fitted lines in each year are: 2008, $y = 24.1x + 2324.6$, $R^2 = 0.566$; 2009, $y = 23.0x + 1908.9$, $R^2 = 0.336$; 2010, $y = 65.31x - 144.5$, $R^2 = 0.604$.

Chapter 4. Conclusions and Recommendations

     In western Oregon, winter canola might have potential as a rotation crop in grass seed crop dominated cropping systems as well as in other areas in need of a high-yielding oilseed crop. The aim of this study was to gain a better understanding of winter canola crop growth and development in this region, with specific focus on: seed yield, seed yield components, oil production, and dry matter and nitrogen partitioning. Winter canola seed yield in western Oregon was influenced by multiple factors including but not limited to: choice of cultivar, spring-N rate, and differences in rainfall among growing seasons.

     Winter canola responded to spring N applications with increased seed and oil yields in the wet environment of western Oregon except under conditions of elevated lodging severity (Ferguson et al., 2015a – Chapter 2). While high N rates resulted in the highest potential seed yields they also produced the greatest risk of lodging and losses in seed yield. Consequently, spring N should be applied at 112 kg N ha^{-1} for winter canola production in western Oregon because this rate best provided high potential seed and oil yield and while minimizing seed and oil yield losses associated with lodging. Seed number m^{-2} was the most influential factor in determining seed yield in winter canola so management practices should be aimed at improving this value. Seed oil content was high but was inversely related to the rate of spring N application, and therefore had a dampening effect on oil yield responses to spring N. Seed protein content was low but was otherwise not affected by spring N. Plant growth regulator applications might be needed to ensure consistent high seed and oil yields of winter canola in the wet environment of western Oregon.

Spring N had multiple effects on dry matter partitioning and seed yield components in winter canola although the responses were differentially mediated by the severity of lodging (Ferguson et al., 2015b – Chapter 3). Tissue N content at the end of flowering was consistently elevated in the above-ground biomass and was an indication of the successful uptake of applied spring N. Biomass was generally increased by N but in this study the results were less consistent as reported by others as a consequence of lodging. Partitioning to seed is important for high seed yield but HI was on the low end of the reported range of values except when lodging was observed. Siliques raceme^{-1} produced by the mainstem raceme was the most important seed yield component measured in the study, and made a major contribution to seed number m^{-2} – the chief determinant of seed yield. Maximum number of siliques raceme^{-1} were produced with the 112 kg N ha^{-1} rate, the same rate recommended for producing high seed yield potential and reducing the risk of lodging losses. The results of this investigation improves our understanding of winter canola dry matter and seed yield component responses under management in the wet environment of western Oregon.

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