A SYSTEMS-BASED APPROACH TO IMPROVE EXPANDING CANOLA PRODUCTION IN TEXAS

A Thesis

by

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ABSTRACT

The United States is currently a net importer of canola (*Brassica napus* L.) and, to become more self-sufficient in production of the commodity, the USDA has prioritized research that will allow expansion of canola production into new areas. Canola offers a possible solution for agricultural producers in Texas and the broader southern region looking for a winter rotational crop for traditionally limited cropping rotations, but the lack of research and data on agronomic management practices specific to the region is a roadblock to adoption.

The first objective of this project was to identify the optimum row spacing and planting density to achieve maximum yield and oil productivity in fall-planted spring canola in the southern US. Replicated studies were carried out at College Station and Perry, TX during the 2017-2018 winter growing season. Treatments included three row spacings (19, 38, and 76 cm), three planting rates (1.7, 3.4, and 5.0 kg ha^{-1}), and two canola cultivars (cv. 'HyCLASS 930' and cv. 'HyCLASS 970'). A 15% reduction in yield was observed at the wide 76 cm row spacing at Perry, showing risk in planting on rows this wide. The lack of differences in yield among the tested planting rates suggests that rates can be dropped as low as 1.7 kg ha^{-1} in this environment, far lower than the commonly recommended 5.6 kg ha^{-1}. The average yield at Perry (2787 kg ha^{-1}) was comparable to the average 2017 yield in Canada (2300 kg ha^{-1}), indicating great potential for fall-sown spring canola production in Texas.

The second objective was to assess potential variety-specific residual chemical effects of wheat chaff on canola germination and early growth in laboratory and outdoor pot studies. In the laboratory study, designed to test the most severe possible effects, canola germination and radicle elongation rates were measured with exposure to aqueous wheat chaff extract solutions at six concentrations (0, 5, 25, 50, 75, and 100 g L^{-1}) in petri dishes. Increasing chaff concentration initially slowed germination, but no differences in germination percentage were observed after four days. Persistent negative effects on radicle growth were observed, as radicle length was 45% lower with exposure to 100 g chaff L^{-1} after four days. In a pot study repeated with chaff from two sources, experimental treatments included two soil types, chaff of 15 wheat cultivars, and untreated controls. Pots were topped with chaff, placed outside for the summer, and planted with canola in the fall. Wheat chaff did not affect germination, but early growth increased by an average of 23% in 13 of 15 chaff varieties. These results indicate that chemical properties of wheat chaff can negatively affect canola seedlings, but these negative effects are unlikely under field conditions.

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CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of chairman Dr. Curtis Adams of the Department of Soil and Crop Sciences, co-chairman Dr. Clark Neely of the Department of Molecular and Environmental Plant Sciences, and committee members Dr. Paul DeLaune and Dr. Emi Kimura of the Department of Soil and Crop Sciences.

All work for the thesis was completed by the student, under the advisement and guidance of the committee members listed in the paragraph above.

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1. INTRODUCTION

Canola (*Brassica napus* L.) has had a rapid rise in popularity and as demand increases globally, acreage and production is increasing in response (USDA-ERS, 2017). The increase in canola's popularity is due largely to its low saturated fat content, for which it is considered a relatively healthy food oil (Canola Council, 2017a). Its value as a livestock feed source and potential biofuel feedstock has also provided marketing opportunities for its oil and meal byproducts (Bonnardeaux, 2007).

Currently, demand for canola in the United States greatly exceeds production, creating a national supply that depends heavily on imports from Canada (USDA-ERS, 2017) The USDA-NIFA Supplemental and Alternative Crops Program is working to close the gap between U.S. demand and domestic production by funding research that aims to increase canola acreage and production (USDA-NIFA, 2018).

Cultivar selection, seeding rates, row spacings, harvest methods, impacts of rotation crops, and other agronomic factors are important considerations when planting canola and can vary depending upon geographic region. Testing these considerations and adapting canola production to fit the needs and climate of the southern Great Plains and the Blacklands region of Texas will be necessary in expanding acreage and maximizing productivity in these regions.

2. LITERATURE REVIEW

2.1 Historical Background and Global Distribution of Canola Production

2.1.1. History of Canola

Canola (*Brassica napus* L.) is one of the most recently developed agronomic crops, with its first cultivar released in Canada in 1974 (McInnis, 2004). It has experienced rapid growth over the past 40 years to become the third largest vegetable oil crop, and the second largest feed meal crop in the world (USDA-ERS, 2017). Canola was developed by Canadian researchers who used traditional plant breeding methods to create an edible form of rapeseed. The name canola comes from the words "Canadian oil" and "low acid". Prior to these breeding efforts, rapeseed was not edible by humans or animals, as high levels of glucosinolates were present in the meal that were shown to slow animal growth at high doses and the oil contained high levels of erucic acid that were harmful to people. The United States banned rapeseed oil for human consumption in 1956 (USDA-ERS, 2017). This ban was lifted with canola development. By internationally regulated standards, canola must contain no more than 2% erucic acid in its fatty acid profile and no more than 30 micromoles of glucosinolates per gram of air-dried oil-free meal (Ali et al., 2009).

2.1.2. Major Production Regions

Globally, canola is most commonly grown in regions that have relatively short growing seasons and dry weather, as shown in Figure 2 (USDA-ERS, 2017). Canada is the world's largest canola producer and exporter, accounting for more than half of the world trade of canola seed, oil, and meal (USDA-ERS, 2017). Canada produced 18.5 million metric tons of canola on 8.05 million hectares during the 2016/2017 growing season, which makes up around 22% of the world's supply (USDA-FAS, 2017). Most of the canola grown in Canada is spring canola. China is the world's second largest producer, accounting for 20% of the world's supply (Hu et al., 2016). India is currently the third largest producer at 12% (Kumar et al., 2009). The European Union and Australia are also major producers, with the European Union producing a combined 33% of the world's supply and Australia producing around 5% (Gervais, 2015). Production data for most countries is reported in terms of rapeseed production, which includes canola production, as many countries develop low erucic acid, low glucosinolate rapeseed cultivars without using the name canola.

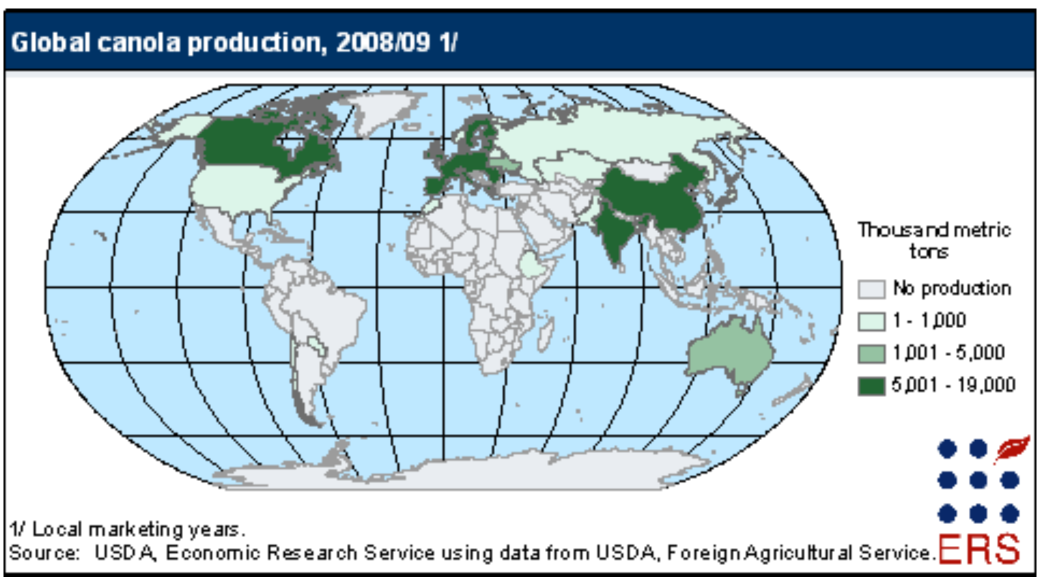

Figure 2.1 Major areas of global canola production, 2008-2009 (USDA-ERS, 2017)

In the United States, canola production is concentrated mainly in the Northern Great Plains region. North Dakota is by far the largest canola producer, making up approximately 80%

of the canola grown in the United States with 690,000 ha harvested in 2017. Oklahoma is the second largest canola producer with 6% of the nation's crop and Idaho is third at 3%. The United States planted 890,000 ha of canola in 2017 (USDA-NASS, 2017b). These production numbers are up from the 690,000 ha harvested in 2016, which yielded a total of 1.4 billion kg of seed (USDA-NASS, 2017b). A similar increasing trend is seen in Texas canola production, with 16,000 ha planted in 2017, compared to 8,700 ha in 2016 (USDA-FSA, 2017).

2.2 Canola Uses and Demand

Processing of canola seed produces two products: oil and meal. Most of the oil is used as edible oil, but in Europe it has also become an important source of biodiesel (European Biomass Industry Association, 2017). Use of canola as an edible oil has increased in popularity due to its low saturated fat levels compared to other commonly used oils (Canola Council, 2017a). It is also cholesterol free and has a high oxidative stability due to its relatively high levels of oleic acid, which increases the its shelf life (Liu and Iassonova, 2012). Canola meal has become valuable as a high protein livestock feed (Huhtanan et al., 2011). Broderick et al. (2015) showed that, while canola meal has lower crude protein than soybean meal, the protein in canola meal is used more efficiently by lactating dairy cows and may improve milk yield over cows fed soybean meal. The potential of canola meal as a livestock feed adds to the value of canola as the market for the oil increases.

Global canola trade has increased over the past several decades as production has increased (USDA-ERS, 2017). More than half of world trade in canola, including seed, oil, and meal, can be attributed to Canada, but because of the abundance of soybean meal and high transportation costs of canola meal relative to value, the trade of canola meal remains limited

(USDA-ERS, 2017). The United States is currently a net importer of canola as domestic consumption greatly exceeds production, as shown in Figure 3; $3.6 billion of canola seed, oil, and meal was imported from Canada in 2016 (Canola Council, 2017c). The European Union, China, Japan, and Mexico are also major canola seed importers (USDA-ERS, 2017). Demand for canola in Europe is increasing because of increased interest in canola oil as a biodiesel feedstock, and Eastern Europe has responded to this demand by rapidly increasing production (van Duren et al., 2015). For example, Ukraine doubled production annually between 2006 and 2008, becoming the second largest canola exporter globally (USDA-ERS, 2017).

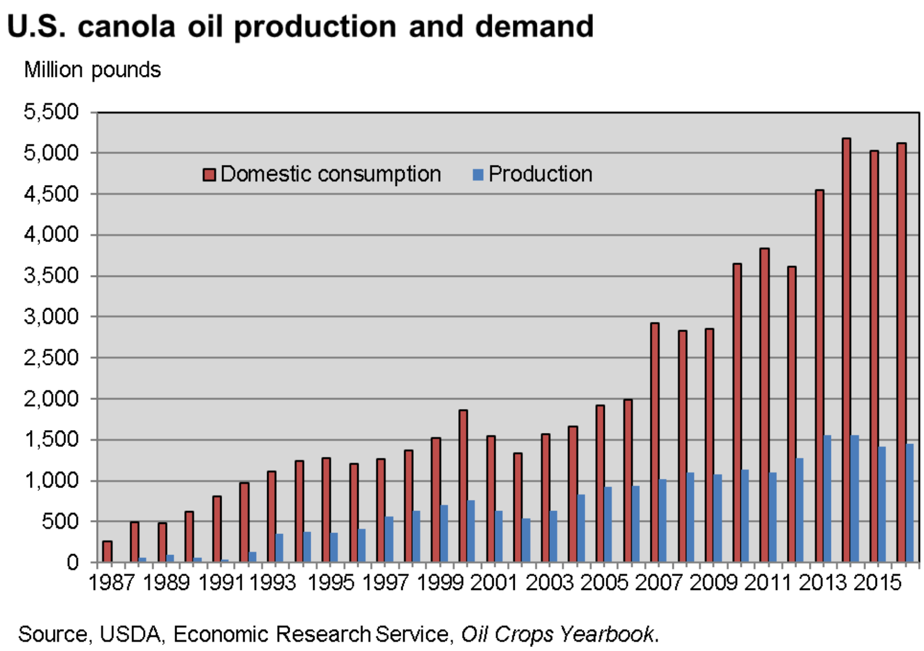

Figure 2.2 United States canola consumption vs. production (USDA-ERS, 2017).

Globally, the USDA estimates that developing countries will account for much of the projected increase in meat and crop demands from 2013 to 2022, as demand for agricultural products will likely increase more rapidly than production (Trostle and Seeley, 2013). Trostle and Seeley (2013) also projected that over 80% of the increase in demand for grains and oilseeds will be the result of increasing demand and consumption in developing countries. This increased demand for oilseeds may lead to more export markets for major canola-producing countries or opportunities for acreage expansion in the future.

2.3 Goals for Future Production

Under the support of the USDA Supplemental and Alternative Crops Competitive (SACC) Grants Program, the United States is actively working to spread canola acreage with the goal of eventually becoming self-sufficient in canola production. The goal of the SACC program is to adapt canola to the diverse growing regions of the United States in order to increase acreage. The SACC program is funding research that aims to increase canola production through germplasm development and testing and improved planting, cultivation, harvesting methods, and farm profitability. Eligible colleges and universities, such as land grant institutions and state agricultural experiment stations; federal agencies; and entities from the private sector may apply for grants. So far, the program has funded canola research in the Southern, Central, and Northern Great Plains; the South and Southeast; the Midwest; and the Pacific Northwest. (USDA-NIFA, 2018).

2.4 Physiology

Seed plants are typically classified according to the type of food reserve they store, either carbohydrate or lipid (Gardner et al., 1985). In oilseed plants, such as canola, lipids are the energy source that support germination and act as an energy reserve that supports early growth. In canola, lipids are accumulated during seed development and are stored mainly as triacylglycerols (Elahi et al., 2016). Selective enzymatic up-regulation and embryonic and seed development gene activity are two major factors affecting oil accumulation in canola seeds (Elahi et al., 2016). Lipid production depends on the availability of sucrose, a product of photosynthesis and precursor for lipid biosynthesis (Elahi et al., 2016). Up-regulating the enzymes involved in sucrose transport and metabolism helps build up carbon reserves to be used by the plant in fatty acid synthesis and later seed oil production and accumulation, as shown in Figure 1 (Elahi et al., 2016).

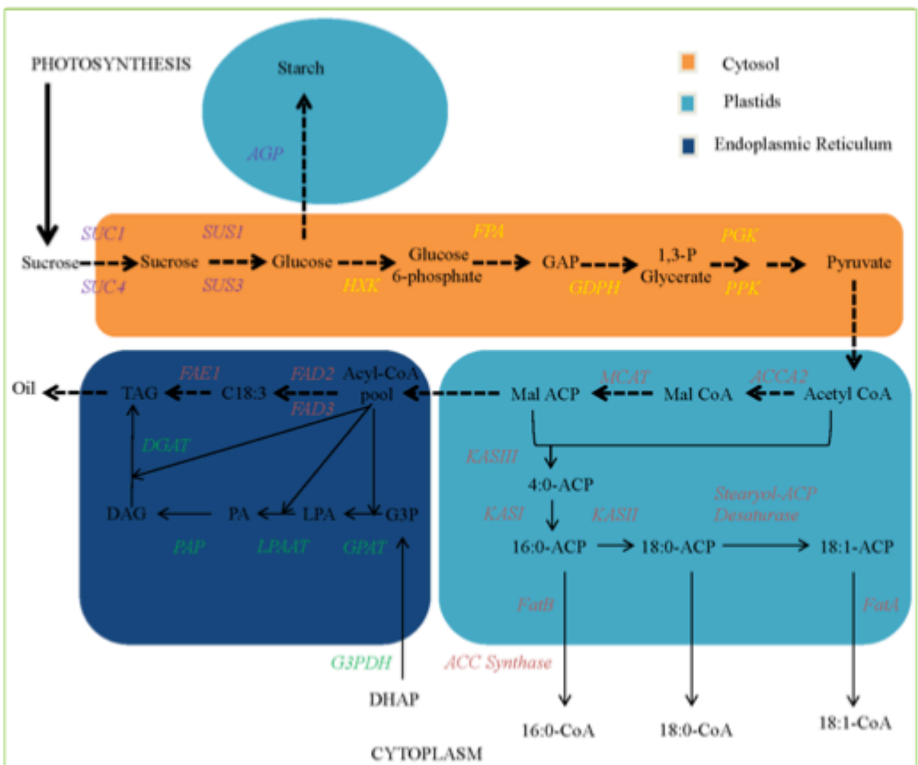

Figure 2.3 Diagram of the regulatory pathways involved in oil synthesis from sucrose in seeds (Elahi et al., 2016).

In development of its metabolites, growth and production rates in canola are closely correlated to the amount of solar radiation incident upon and captured by the leaves. As canopy coverage and leaf area index (LAI) increase, the amount of solar radiation that the plant is able to capture increases. In general, in the case of winter canola, the LAI increases at a slow rate through the autumn and winter and then increases rapidly during the spring where it reaches a maximum shortly after flowering is initiated (Walton et al., 1999). Canola's canopy development and vegetative growth stages end at bolting, when rapid growth of the main stem begins and lasts about one to two weeks (Knott, 2017). Floral initiation begins directly after bolting. Typically, flowers that form during the first 18-21 days after floral initiation will produce viable pods (Thomas, 2012). Flowers developed later are less likely to produce viable pods, but may do so if the plant experiences water stress during early flowering (Thomas, 2012). Longer periods of flowering are generally not beneficial, as they can cause the plants to devote more energy to producing flowers that will not develop productive pods.

Dry matter production in canola plants increases rapidly after canopy closure is reached and then slows during pod fill as leaves begin to senesce (Walton et al., 1999). Root growth continues until reaching a maximum density late in the flowering stage, where roots may extract water and nutrients to a depth of around 1.65 m. Most of the water and nutrients utilized by canola plants, however, are extracted from the top 1.2 m of the soil profile (Nielson, 1997). Water stress that occurs during vegetative growth stages can cause a number of issues in canola, such as reductions in stem height, leaf number and area, total plant dry matter, net CO_2 assimilation, and metabolite production (Qaderi et al., 2012).

Canola seed oil concentrations can range from 30-50% and are affected by a number of environmental factors such as water deficit (drought) stress, heat stress, and high nitrogen (N) supply (Walton et al., 1999). With both drought and heat stress, the earlier in the growing season the stress occurs, the more time the plant has to recover before the reproductive stage begins and yield is negatively impacted. Stress closer to or during the reproductive stage is more likely to compromise yield (Angadi et al., 2000). Ahmadi and Bahrani (2009) saw seed yield reductions of 29.5% and oil yield reductions of 31.7% when canola plants were water-stressed at flowering. Drought stress during vegetative or seed-filling stages typically will not cause a reduction in yield (Tohidi-Moghadam et al., 2009). But Taylor et al. (1991) showed that irrigated canola produced seed with oil concentrations up to 4% higher than rain-fed canola that received less than half the amount of water as the irrigated canola.

Because it is a cool-season crop, canola is sensitive to high temperatures and heat stress. Temperatures over 27°C can cause heat stress in spring canola, though as with water stress, tolerance may vary depending on cultivar and growth stage (Morrison and Stewart, 2000). During flowering, temperatures over 29.5°C can cause seed yield losses (Morrison and Stewart, 2000). Gan et al. (2004) found that heat stress at 35°C caused an average decrease in seed weight of 22%. High temperatures lead to accelerated plant development, which reduces both the length of the growth period and the yield potential (Entz and Fowler, 1991).

Several studies have reported decreased seed oil concentrations with increased N applications (Ahmad et al., 2007; Brennan and Bolland, 2009; Al-Solaimani et al., 2015). This response to increased N is coupled with, and likely a result of, an increase in seed protein concentration that is also seen with increased N (Hao et al., 2004). With high N availability, there is increased production of proteins and protein precursors that contain high levels of N. The production of proteins may also compete for photosynthates, leaving fewer resources available for oil synthesis (Hao et al., 2004). Though it causes a decrease in oil concentration, N fertilizer promotes seed yield increases, often leading to an overall increase in oil yield from the crop (Taylor et al., 1991).

2.5 Agronomics

2.5.1. Field and Cultivar Selection

Canola can generally be grown on a wide range of soil types, but good surface or subsurface drainage and a soil that does not crust are important as canola tends to be sensitive to waterlogging and crusting may hinder seedling emergence (Kandel and Knodel, 2011). Canola can tolerate soil pH levels from 5.5 to 8; however, in soils over a pH of 7, some nutrients may become less available and applications of sulfur (S), iron, and zinc may be needed to increase yields (CSU Extension, 2014). Compacted soil, such as a plow pan, may disrupt normal rooting patterns and reduce rooting potential (CSU Extension, 2014).

Cultivar selection is important, as winter and spring cultivars are generally grown in different regions and breeding efforts are generating varieties better adapted to new regions. Spring canola is planted in Canada and the Northern Great Plains of the United States in April to early May and harvested in September (Coleman, 2016). Winter canola is not planted in the Northern Great Plains region due to its susceptibility to freeze damage (Kandel and Knodel, 2011). Winter canola is more commonly planted farther south. Winter canola is planted in August to October or six weeks before the first killing frost, grows over the winter and spring, and is harvested before the onset of high summer temperatures (Assefa et al., 2014). In far southern regions of the United States, including South Texas where research is ongoing, fall-planted spring canola seems to be a viable option. This option may be best for the far southern region because winter temperatures are often not low enough for successful vernalization of winter varieties and summer temperatures are too high to be favorable for spring-planting of spring varieties (Neely, 2014).

Producers now have more options for weed control with Roundup Ready®, Liberty Link®, and Clearfield® canola cultivars now available. With these options, producers can use glyphosate (Roundup®), glufosinate (Liberty®), or imazamox (Clearfield®), respectively, to control emerged weeds without harming canola plants.

Traditional canola varieties are open-pollinated, but hybrid varieties are now available. Open-pollinated varieties produce seed through self-pollination or cross-pollination, and if they are isolated from other varieties, will produce inbred plants from which seed can be saved and reliably replanted (Clayton et al., 2009). Due to heterosis, hybrid varieties often have a yield advantage over conventional varieties (Brandt et al., 2007). Hybrid varieties also tend to have a greater response to higher levels of applied N, suggesting higher N use efficiency and recovery (Brandt et al., 2003). An Australian study found that hybrid varieties out-performed open-pollinated varieties in favorable environments with high rainfall and long growing seasons, but in areas with low rainfall and low yield-potential there were no differences (Zhang et al., 2016). In Canada, the Prairie Canola Variety Testing program compared 17 open-pollinated varieties and 24 hybrid varieties over three years and three zones (long, mid, and short season zones). The hybrid varieties out-yielded the open-pollinated varieties by 12-23% in every year and zone (Goodwin, 2006). Large-scale commercial canola production in Canada has seen a similar trend with an average hybrid yield 23% higher than that of open-pollinated varieties in the years 2001-2004 (Goodwin, 2006). In the United States hybrid varieties are gaining in popularity, especially in high-yielding environments, though open-pollinated varieties are still the dominant choice for producers in the winter canola market (Stamm, 2016).

2.5.2. Tillage Systems

Canola can be planted in conventional, strip-till, or no-till systems. According to a 2012 survey, approximately 40% of canola farmers in Western Canada used a no-till system and 30% used minimum or reduced tillage (Canola Council, 2017b). One advantage of using a no-till system for canola production is that the residues left on the surface help maintain soil moisture. This is important during planting, as canola seeds are very small in size and must be planted at a shallow depth to avoid emergence issues; additionally, maintaining soil moisture at the surface ensures better germination (Harker et al., 2012). Conventional tillage can aid in weed control and make soil applications of herbicides and fertilizers easier, but can also deplete soil moisture and degrade soil structure (Blevins et al., 1971). A grower's choice of tillage system is often based on personal preference, soil type, erosion potential, tillage history, and other considerations (Canola Council, 2017b).

2.5.3. Planting

Choosing the appropriate planting date for a specific location is crucial to a successful canola crop (Gusta et al., 2004; Adamsen and Coffelt, 2005; Holman et al., 2011). When planted too late, winter canola may be more susceptible to winter kill since the smaller plants may not have extensive root systems or sufficient energy reserves stored; generally, plants need five to eight true leaves for winter survival (Stamm and Ciampitti, 2017). When planted too early, too much top growth may also affect winter survival as excessive stem elongation could lead to physical damage of the unprotected crown (Stamm and Ciampitti, 2017). The general rule in many areas, including Oklahoma, is to plant winter canola six weeks prior to the first killing frost to allow for enough growth for winter hardiness (Boyles et al., 2004). In canola growing regions of Canada and other similar environments, spring canola can be damaged by frost if planted too early in the spring (Angadi et al., 2003).

Another important consideration when planting canola is planting depth. Canola seeds are smaller than those of many other crops, and therefore must be planted at a shallower depth to ensure successful emergence. The common recommendation is to plant at a depth of 1.3-2.5 cm (0.5-1.0 in), though larger hybrid seed may be planted down to 3.8 cm (1.5 in) (Kandel and Knodel, 2011).

While Harker et al. (2014) found that increasing seed size in canola was positively associated with early biomass, they also observed a negative linear relationship between seed size and days to flowering. The increase in early biomass seen with larger-seeded varieties increases the crop's competition with weeds, which results in earlier flowering and a shortened flowering period (Harker et al., 2014).

Broadcasting or spreading is not recommended when planting canola, as it does not allow for sufficient seed-soil contact and often leads to variable emergence and poor stands (Kandel and Knodel, 2011). The University of Saskatchewan suggests seeding at a rate of 5.6 kg ha^{-1} (5 lb ac^{-1}), but seeding rates can range from 1.7 to 6.7 kg ha^{-1} (1.5-6.0 lb ac^{-1}) depending on the planting equipment used and the cultivar's thousand-seed weight (Shirtliffe, 2009). Canola seeds generally range from around 198,000-254,000 seeds kg^{-1} (90,000-115,000 seeds per pound) (Brown et al. 2008), so planting rates are typically around 336,500-1,700,000 seeds ha^{-1}. This wide range in seeding rates is due partially to the range of canola seed sizes. Mid-sized open-pollinated seeds are around 0.7-2.0 mm in size, while the larger hybrid seeds are often over 2.0 mm (Hwang et al., 2014). Hybrid canola can achieve 90% of its maximum yield at 45 plants m^{-2} while open-pollinated varieties require 90 plants m^{-2} to produce 90% of its maximum yield

(Shirtliffe, 2009). Canola does have the ability to compensate for lower populations by increasing branching, so seeding rates can be flexible (Vann et al., 2016). A stand of 40-80 plants m^{-2} can maintain yield potential when plant populations are uniformly distributed (Angadi et al., 2003).

Row spacing is another important consideration when planting. While several studies have shown that highest yields can be achieved in 15 cm rows compared to wider 48-61 cm row spacings, most studies have found no significant differences in the yields of canola planted in 15 and 30 cm row spacings (Kondra, 1975; Christiansen and Drabble, 1984; Johnson and Hanson, 2003). Most data on the relationship between row spacing and yield comes from research conducted in Canada, North Dakota, and other larger canola producing areas so there is a lack of such data for Texas.

2.5.4. Winter Survival

Winter survival of canola is a primary challenge facing agricultural producers in the Central Great Plains, who are increasingly turning to canola to help break weed and disease cycles in their wheat-based cropping systems (Holman et al., 2011). In central and south Texas, however, severe cold temperatures are less common and winter survival is less of a concern for producers. In South Texas, planting in late October to early November, 2-3 weeks prior to typical winter wheat planting, gives the crop enough time to develop a root system and sufficient growth to withstand winter temperatures (Livingston et al., 1995). Cold tolerance can vary among varieties, so some varieties may be better adapted to colder areas than others (Neely et al., 2015). Growers have reported decreased winter survival when crown heights were elevated above the soil surface before low winter temperatures set in, but this relationship is not solidly supported by research (Assefa et al., 2014; Holman et al., 2015). Abundant fall growth and establishing a large plant may also be important for winter survival and can be achieved by earlier planting in western KS (Holman et al., 2015).

2.5.5. Harvesting

One of the biggest challenges facing canola growers is harvesting the crop at maturity while minimizing losses from pod shattering (Gan et al., 2008). Because canola is prone to shattering once it reaches maturity, growers have a much smaller timeframe for harvest compared to other crops. Typically, growers have three options for harvesting: direct harvest of standing plants, windrowing, and pushing. Direct harvest, or direct combining, is the least time consuming option and can lower costs. Producers opting for direct harvest sometimes use desiccants to dry down the crop and increase uniformity at harvest if conditions are wet and cool (Jenks, 2008). The EPA approved the herbicide Reglone (diquat dibromide) for use as a desiccant on canola in 2010 (EPA, 2010). Windrowing is similar to hay cutting, where the crop is cut, swaths are condensed into narrow rows, and allowed to mature. Because it is done at a higher seed moisture that direct harvest, well-timed windrowing may reduce seed loss due to shattering (Cavalieri et al., 2016). Pushing is also an option in which plants are mechanically lodged and allowed to mature without being cut off from their root systems. There are no significant differences in yield between pushed and windrowed canola crops (Irvine and Lafond, 2010).

Average canola yield in the United States for 2016 was 2044 kg ha^{-1} (1824 lb ac^{-1}) (U.S. Canola Association, 2017). Spring canola cultivar trials in South Texas yielded an average of 1184 kg ha^{-1} (1056 lb ac^{-1}) in 2017 (Neely et al., 2017a). Canada averages around 2240 kg ha^{-1}

(40 bu ac^{-1}), though yields in the 2800-3900 kg ha^{-1} (50-70 bu ac^{-1}) range are becoming increasingly common with improved management practices (Hart, 2015).

2.5.6. Fertility

The N, phosphorus (P), and potassium (K) requirements of canola are similar to those of small grains (Kandel and Knodel, 2011). Compared to most crops, however, canola has a high S requirement. Canola seed has a high protein content with a relatively large proportion of sulfur-containing methionine and cysteine (Malhi and Gill, 2002). Sulfur is immobile in plants, and deficiencies that occur at any stage of canola growth can negatively impact yield (Malhi and Gill, 2002).

For profitable canola production, applications of N and P are necessary (Brennan and Bolland, 2009). Brennan and Bolland (2009) found that there is a significant interaction between N and P, and the amount of N needed for canola to reach 90% maximum yield increases as the amount of P applied increases. Phosphorus applications are generally needed to increase yield if soil levels are less than 5ppm (Brown et al., 2008). According to the Canola Council of Canada (2017b), canola needs 3.25-4 kg ha^{-1} of available nitrogen per bushel of seed yield. A 2009 study determined the N requirement of hybrid canola to be 50-60 kg N ha^{-1} (Smith et al., 2010). Potassium deficiencies are typically uncommon, but may be observed on sandy soils, especially if the field is used in a system where a majority of the crop biomass is removed each year, as much of the K taken up by plants is returned to the soil through the crop residue. Symptoms of K deficiency in canola may not be seen until amounts in the soil are less than 170 kg ha^{-1} (Canola Council of Canada, 2017b)

Micronutrient deficiencies are less common and research has not shown a significant response to micronutrients such as zinc, iron, copper, and molybdenum (Brown et al., 2008). Soil pH is often a causal factor of micronutrient deficiencies, with manganese and zinc deficiencies most likely to occur in high pH soils (Norton, 2011). Application of micronutrients that attempt to correct deficiencies in canola may be more likely to cause toxicity problems than help the crop (Brown et al., 2008).

2.6 Allelopathy and Other Residual Effects of Wheat on Canola

Allelopathy is an ecological phenomenon in which biochemicals released from parts of one plant, such as roots or residues, have an effect, either harmful or beneficial, on another plant species (Ferguson et al., 2013). In crop plants, allelopathic chemicals are typically secondary metabolites that enter the soil through root exudates, leaching from plant tissues during wet conditions, and leaching from decomposing plant residues (Lam et al., 2012). Allelopathic chemicals can be beneficial in weed suppression (Jabran et al., 2015), but can also have negative effects on the germination and seedling growth of crop plants. Wheat, which is the most commonly grown winter crop in Texas, is known to have allelopathic properties, the effects of which have been studied on some rotational crops including cotton (*Gossypium hirsutum*), rice (*Oryza sativa*), canola, and several weed plant species (Wu et al., 2001; Hicks et al., 1989; Yaseen and Hussain, 2014). Yaseen and Hussain (2014) observed significant decreases in rice plant height, spike number and length, number of seeds per spike, internode length, and leaf length and width when aqueous extracts from wheat root and shoot straw were applied to the soil. A similar greenhouse pot study showed that the addition of TAM 104 wheat stubble to soil in pots caused decreases in cotton germination and seedling emergence by as much as 26%

(Hicks et al., 1989). Bruce et al. (2006a) observed decreased yields in canola planted into wheat stubble, as seedlings produced longer hypocotyls and reduced leaf number and biomass. These effects, however, seem to be caused by the physical impact of the wheat stubble and not a chemical impact. The limited data on canola suggests that the crop is sensitive to wheat allelochemicals, but the effects have been variable and largely dependent on the varieties of both the wheat and canola, according to a study using varieties common to Australia (Bruce et al., 1999).

Wheat can have a number of other residual effects as well, both beneficial and negative. Wheat stubble can intercept applied herbicides, potentially reducing the efficacy of preemergence weed control (Ghadiri et al., 1984). Wheat residue extracts have been shown to inhibit root growth in ragweed (*Ambrosia artemisiifolia*) and pitted morning glory (*Ipomoea lacunose*) (Liebl and Worsham, 1983). Effects of decomposing wheat residue on soil pH seem to be minimal (Xu and Coventry, 2003), but decomposing wheat straw can positively impact both the size and composition of microbial communities, which may help to increase soil organic matter content in the long-term (Bastian et al., 2009; Ocio et al., 1991). Additionally, Zavalloni et al. (2011) showed that soils treated with wheat straw had higher microbial C and N levels and lower soluble organic N than untreated soils, effectively decreasing the leaching potential of N in the soil.

2.7 Canola in Texas

2.7.1. Areas of Production and Acreage

Canola is not widely grown in Texas, but with a processing plant for canola now located in Lubbock, Texas, growers have begun to consider the crop as a viable rotation option. Some producers also see canola as an attractive option because of the crop's price advantage over wheat. In 2016, the price of canola in the United States was around \$0.29 kg^{-1} (\$6.50 bu^{-1}) while the price of winter wheat was \$0.15 kg^{-1} (\$3.60 bu^{-1}) (USDA-NASS, 2017a; Anderson, 2016). Currently, the Rolling Plains is the primary region in Texas for canola production, due largely to their proximity to crushing facilities and environmental similarity to Oklahoma, the country's second largest canola producing state.

2.7.2. Crushing and Processing

The nearest canola intake facility for growers in Texas is the Archer Daniels Midland (ADM) plant in Lubbock (Pehr, 2014) and many grain elevators and cooperatives in Oklahoma have also recently become canola buyers (Oklahoma State University, 2017). Having a plant relatively close to most producers greatly reduces transportation costs, which had previously been a major deterrent to many farmers considering canola production (Mattson et al., 2007). As canola hectares increase, more local elevators are apt to accept canola and create more local delivery points.

2.7.3. Potential as a Rotational Crop

One of the biggest advantages of growing canola in Texas is for its rotational benefits in wheat production systems, as a major issue in continuous wheat cropping systems is the persistence of grassy weeds in the fields (Bushong, 2012). While expanding technologies, such as Clearfield wheat varieties, which are resistant to the herbicide Beyond (imazamox), are making grassy weed control in wheat easier, producers still have a limited number of options. Well-established Roundup-ready, Liberty Link, and Clearfield canola varieties allow growers to control grassy weeds with effective herbicides like glyphosate, glufosinate, and imazamox, respectively, that cannot be used post-emergence on wheat (K-State Research and Extension, 2012). Rotating wheat with canola also gives wheat producers more grass herbicide options, such as sethoxydim (Poast), clethodim (Select), and quizalofop p-ethyl (Assure II), which are often more cost-effective options.

Rotating wheat with canola may be beneficial for breaking cycles of disease (Kirkegaard et al., 2008). For example, *Rhizoctonia solani* is a fungus that causes Rhizoctonia root rot in wheat. Studies in a cereal growing region of Western Australia showed that rotation with canola can greatly reduce the amount of Rhizoctonia inoculum in the soil and thus reduce the amount of the disease seen in the next wheat crop because of the suppressive effects that canola root residues have on the fungal inoculum (Hüberli, 2015; Smith et al., 1999).

Integrating a canola rotation into a wheat system can improve soil structure. Canola roots encourage stable aggregate formation and macropore creation (Chan and Heenan, 1996), while the longer taproot of canola can take up water from depths greater than that accessible to wheat root systems. Creation of macropores in the soil from canola root systems can create more space for water to be stored and accessed by the next wheat crop and provides roots with spaces to grow (Passioura, 1991). This deeper root system also means that canola takes up less water from the upper region of the soil profile than does wheat, which increases the amount of water available to the following wheat crop (Cutforth et al., 2012).

Rotating canola with wheat can lower the N requirement of the following wheat crop. Wheat planted after canola requires less N than wheat following wheat or a pasture rotation (O'Sullivan et al., 2015). O'Sullivan et al. (2015) suggested that this may be due to relatively low nitrification rates in the rhizosphere of canola, which would conserve N in the form of ammonium, increasing immobilization rates, and causing N to be stored in the soil for utilization by the following wheat crop.

2.8 Conclusions

Despite canola's rapid growth globally over the past 30 years, the United States has been slow to increase acreage and production. Current global production is centered in Canada and China, but acreage is expanding in areas such as Eastern Europe and Australia to keep up with increasing demand. In the United States, limited crushing locations and processing facilities are still a major limitation to production, but interest in the crop is increasing. Increased interest is largely due to the benefits of canola in a wheat rotation and potential profitability of canola over wheat at typical commodity prices (White, 2015). This increased interest has enticed more grain elevators to accept canola, helping make the crop a more feasible option, including in Texas.

Because of climatic differences between Texas and the major canola producing regions of the United States, fall-planted spring canola may be the most promising option for canola producers in the Texas Blacklands and South Texas, where winters are not reliably cold enough for successful winter canola production and summers are too hot for spring-planted spring canola. Still, winter canola is likely more suited to the northern regions of the state and the rest of the Southern Great Plains. With data on both currently lacking, more research is needed in this area in order to successfully establish canola as a rotational crop in Texas. Cultivar testing will be necessary to identify varieties that are adapted to the different regions of the state. Similarly, the optimal seeding rates and row spacings for canola production in Texas will need to be determined as they may differ from those of other canola producing areas, such as Oklahoma and the Northern Great Plains, that have different climates and seasons. With more research, best management practices can be established, specifically for unique regions of Texas to make canola a practical choice for producers looking to diversify their cropping systems and spread out economic risk.

3. FALL-PLANTED SPRING CANOLA IN THE SOUTHERN U.S.: EFFECTS OF ROW SPACING, PLANTING RATE, AND CULTIVAR ON GROWTH AND YIELD

3.1 Introduction and Objectives

Canola (*Brassica napus* L.) is a form of rapeseed, which has long been cultivated for its oil-rich seed. Natural or wild-type rapeseeds contain erucic acid and glucosinolates, which lower the feed and food value of the oil and byproduct materials. Following breeding efforts to reduce erucic acid (<2%) and glucosinolate seed concentrations (<30 µm), the resulting germplasm became known as canola. Canola was granted Generally Recognized as Safe (GRAS) status by the FDA (USDA-ERS, 2017) in 1985 and soon thereafter, researchers in Canada, the United States, and other locations began to consider canola for its potential as an alternative oilseed crop (Belsie, 1990).

Large-scale adoption of canola in the U.S. has occurred primarily in North Dakota and the surrounding region (U.S. Canola Association, 2017), though canola production is expanding in other states. Winter canola has become an established crop in Oklahoma, with canola planted on an average of 69,000 ha annually from 2013 to 2017, making it the second largest canola-producing state (USDA-NASS, 2016; USDA-NASS, 2017). Successful production of winter canola in Oklahoma, which primarily has occurred in winter wheat cropping systems, may lead the way for integration of canola into winter cropping systems in nearby areas of the southern U.S. In other areas, canola has been shown to have a variety of benefits in rotation with winter crops, including increased wheat yield (Kirkegaard et al., 2008), increased soil water availability to subsequent crops (Cutforth et al., 2012), and breaking pest and disease cycles (Johnston et al., 2002). But before canola can play a significant role in agriculture in the southern U.S., studies are needed to determine region-specific Best Management Practices (BMPs) for the crop.

Row spacing and planting density have been studied in major canola producing regions. Johnson and Hanson (2003) compared 15 and 30 cm row spacings in spring canola in North Dakota across five different environments, using open-pollinated, conventional, hybrid, and transgenic cultivars. No difference was found in seed yield with row spacing among the cultivars examined (Johnson and Hanson, 2003). Xie et al. (1998) also reported no differences in yield between 25 and 38 cm row spacings in Canada. Though there are potential benefits to wide row spacings, such as reduced input costs, easier stubble management, and use of row crop equipment (Harries et al., 2015), several Canadian studies have shown decreasing yields with increasing row spacing (Kondra, 1975; Christiansen and Drabble, 1984; Morrison et al. 1990). An Oregon study showed lower yields when planting on 76 cm rows compared to 15 cm rows, but results were not consistent over both years of the study (Wysocki and Sirovatka, 2009). In Oklahoma, narrow rows were also preferable as Showalter (2017) showed that narrow row spacings and reducing seeding rates may increase winter survival and yield in winter canola. Angadi et al. (2003) observed no yield differences with plant densities between 80 and 40 plants m^{-2} in 23 cm row width if the low plant population density was uniformly distributed within the row, though yield was reduced when plant population was unevenly distributed. A North Carolina study showed that increasing row spacing can allow for inter-row cultivation to decrease weed pressure, which can increase yields when weed pressure is high (Vann et al., 2016). Degenhardt and Kondra (1981) tested planting rates of 3, 6, and 12 kg ha^{-1} and found that rate had no significant effect on seed yield. These studies suggest that row spacing and plant density can be flexible in yield optimization of canola. However, there is limited information on wider row spacings and lower planting densities and none from our target region of the southern U.S., where spring canola may be grown over the winter months.

Agricultural producers in the southern U.S. need additional rotation options for their traditionally limited cropping rotations. Canola offers a solution to this problem. Because mild winters in the southern U.S. generally create a barrier to consistent vernalization of winter canola, the best option may be to plant spring canola in the fall since no vernalization is required (Neely et al., 2016; Neely et al., 2017a). While fall-planted spring canola is common in Australia (Australian Government, 2011), there are currently no published, peer-reviewed studies on row spacing and planting density for fall-planted spring canola production in this region. The lack of research and data on agronomic management practices for canola specific to the region is a roadblock to adoption. The objective of this study was to identify the optimum row spacing and planting rate to achieve maximum yield and oil productivity in fall-planted spring canola in the southern U.S.

3.2 Materials and Methods

Replicated studies were carried out during the 2017-2018 growing season at two locations in Texas: Perry (31°25'18.57" N, -96°54'13.49" W) and College Station (30°31'6.13" N, -96°25'7.06" W) (Figure 3.1). These locations have a warm and humid climate, representative of the southern U.S. The soil type at the Perry location is a Crockett fine sandy loam (fine, smectitic, thermic Udertic Paleustalfs), and the College Station location has a Belk clay (fine, mixed, active, thermic Entic Hapluderts). Canola was planted following corn at College Station and oats at Perry. Table 3.1 summarizes trial location data.

Figure 3.1 Trial locations.

Study treatments included three row spacings, three planting rates, and two spring canola cultivars in a randomized complete block design (RCBD) with three replications. Plot size was 4.6 × 9.1 m. The trial was planted with a Hege 500 (Hege Company, Waldenburg, Germany) single cone, double disk plot drill (6 rows, 19 cm spacing) with dividers used to combine rows for different spacings. The row spacing widths tested were 19, 38, and 76 cm, and the planting rates tested were 1.7, 3.4, and 5.1 kg ha^{-1}. The cultivars were cv. 'HyCLASS 930' and cv. 'HyCLASS 970', which are both glyphosate resistant spring canola hybrids. Both trials were conventionally tilled and managed without irrigation.

Table 3.1 Summary of trial location data

Location	College Station, TX	Perry, TX
Coordinates	30.5°N 96.4°W	31.4°N 96.9°W
Soil Type	Belk Clay	Crockett fine sandy loam
Date Planted	11/07/2017	11/03/2017
Date Harvested	04/19/2018 HyCLASS 930 04/30/2018 HyCLASS 970	05/08/2018 HyCLASS 930 05/14/2018 HyCLASS 970

Pre-plant soil samples indicated that there was 96 kg ha^{-1} N, 316 kg ha^{-1} P, and 1843 kg ha^{-1} K in the top 91 cm at College Station and 52 kg ha^{-1} N, 29 kg ha^{-1} P, and 166 kg ha^{-1} K in the top 30 cm of at Perry. At College Station, clethodim (3-chloro-2-propen-1-oxypropanimidoyl-5-2-ethylsulfanylpropyl-3-hydroxy-2-cyclohexen) at 438 g ha^{-1} and paraquat (1,1'-dimethyl-4,4'bipyridinium dichloride) at 2340 g ha^{-1} were applied prior to planting to control volunteer corn (*Zea mays*) and henbit (*Lamium amplexicaule*). Glyphosate (N-phosphonomethyl glycine) was applied at planting at 1750 g ha^{-1} for weed control. In late January, plots were top-dressed with 33.6 kg N ha^{-1} (urea 46-0-0) and 0.00117 g ha^{-1} of glyphosate. At Perry, 1750 g ha^{-1} glyphosate was sprayed one month after planting for weed control. Plots were top-dressed in early February with 51.6 kg N ha^{-1} (urea 46-0-0), 17.4 kg P ha^{-1} (0-30-0), and 1.35 kg Zn ha^{-1} and 0.6 kg N ha^{-1} (4-0-0-9Zn). Fertilizer applications were made using soil test recommendations based on samples collected to a depth of 30 cm at Perry and 91 cm at College Station.

Field and laboratory evaluations were carried out as summarized in Table 3.2. Crown heights were measured approximately two months after planting, when plants were around the four-leaf stage. Stem diameters and plant heights were measured in the spring at harvest using a meter stick, taking the average of five plants per plot. At harvest, lodging was estimated visually as percent lodged plants per plot. Seed was harvested from the entire length of the center 1.5 m of each plot with a Wintersteiger (Wintersteiger Ag, Ried, Austria) Classic plot combine with a 1.5 m header. Seed was dried down in a 50°C oven for 48 hours and then weighed to determine yield per plot. Test weight and moisture were measured using a DICKEY-john GAC 2100 Agri grain analysis computer (DICKEY-john, Auburn, IL) and used to adjust yields to 8% moisture. Seed subsamples from each plot were packaged and sent to the Brassica Breeding Program at University of Idaho to be analyzed for oil content using Near Infrared Spectroscopy. Oil content was analyzed using a Foss XDS Rapid Content Analyzer (Foss, Eden Prairie, MN) in which spectra are collected and component estimates are generated with ISIScan 3.20 software (Infrasoft International LLC, State College, PA). Calibration was developed using WinISI 4.4 software (Infrasoft International LLC) using the software's modified partial least squares regression method and approximately 100 canola seed samples with known protein, oil, and moisture contents. Yield and oil content were used to determine oil productivity in kg oil ha^{-1}.

Table 3.2 Field and lab evaluation data collected.

In-Field Evaluations	**In-Lab Evaluations**
Stand evaluation (plants m^{-1})	Seed yield (kg ha^{-1})
Crown height (cm)	Seeds pod^{-1}
Stem diameter (cm)	Pods plant^{-1}
Plant height (cm)	Single seed weight (g)
50% Bloom date	Oil content (%)
Lodging (%)	

A subsample of three plants was taken from each plot at harvest. Plants were threshed to obtain seed weight per sample. Individual seed weights for each plot were estimated using the weight of 500 seeds from the plot's subsample. Number of pods per plant, individual seed weight, and total seed weight per sample were used to determine seed number per pod.

Statistical analysis was conducted using SAS 9.4 (SAS Institute, Cary, NC). PROC GLIMMIX was used to conduct an ANOVA with LSMEANS for mean separation analysis, adjusted using the Tukey method (Appendix A-1). In the statistical model, treatment factors were considered fixed effects, while experimental block was considered a random effect. Initial analysis revealed a large location effect on yield and, because of the large difference in yield between the locations, each location was analyzed individually. Data was checked for compliance with the assumption of normality using the UNIVARIATE procedure in SAS. A probability threshold of 0.05 was used to determine statistical differences. Interactions between all experimental treatments were tested, including three-way interactions, which were not significant and thus removed from the model.

3.3 Results

3.3.1. Weather

Minimum and maximum temperatures and precipitation at each location over the project period (November 2018-May 2018) are shown in Figures 3.2 and 3.3. Temperatures below freezing were experienced in mid-winter in both locations, and especially in Perry, where temperatures dropped to freezing or below on 32 days over the growing season. College Station experienced 25 days with temperatures at freezing or below. Both locations reached their lowest temperature on January 17, dropping to a low of -12.2°C at Perry and -9.4°C at College Station. Cooler than average spring temperatures likely contributed to the high yields and oil content.

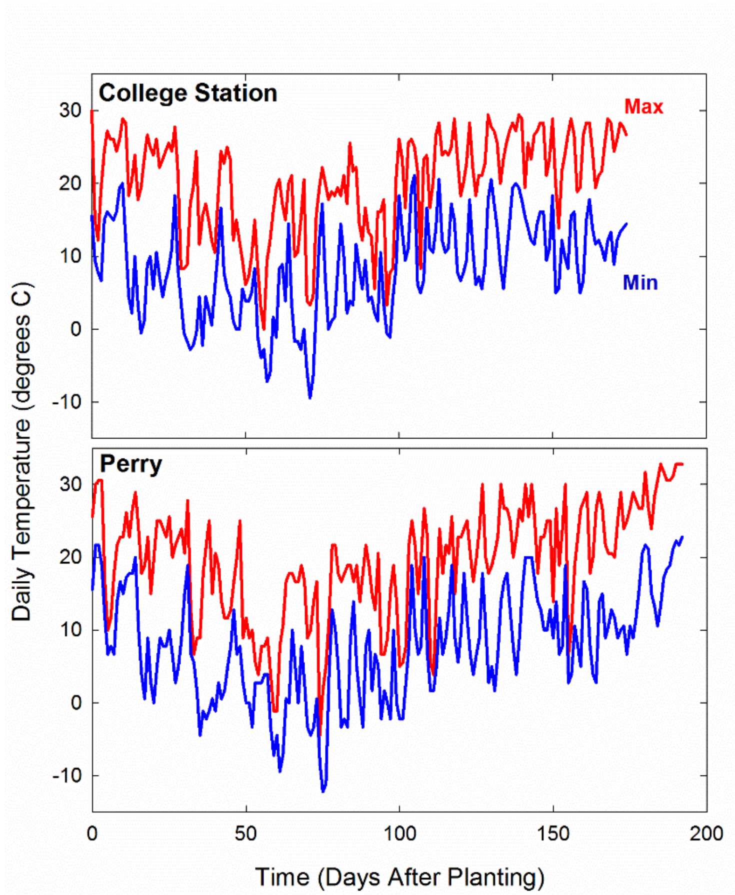

Figure 3.2 Daily minimum and maximum temperatures at both project locations over the trial period (National Weather Service, 2018).

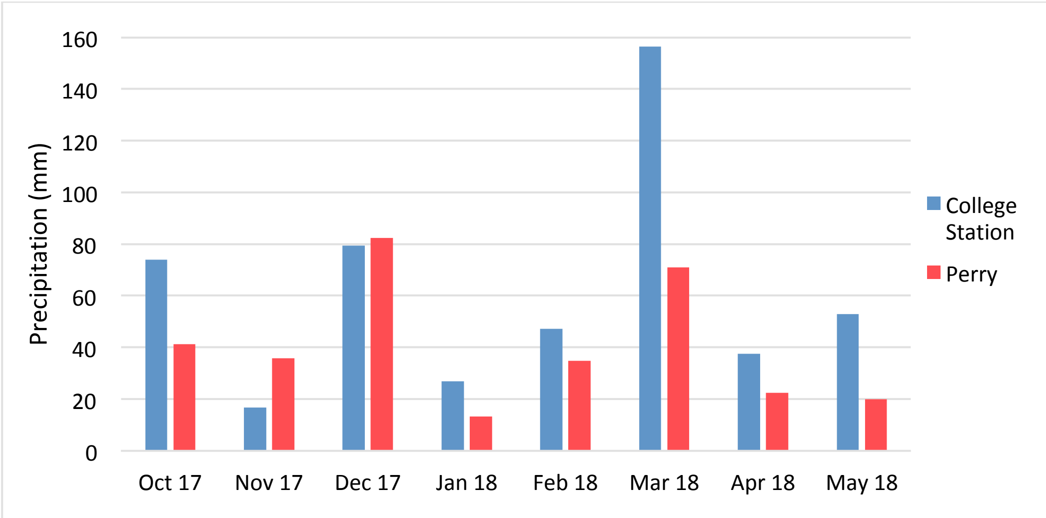

Figure 3.3 Monthly precipitation at both locations over the trial period (National Weather Service, 2018 and USDA-ARS Temple, TX, unpublished).

3.3.2. Yield

Mean seed yield was 1741 kg ha^{-1} greater in Perry than in College Station. In College Station, HyCLASS 970 yielded 195 kg ha^{-1} greater than HyCLASS 930 (Table 3.3). At the Perry site, there was an interaction between cultivar and planting rate due to opposite trends in cultivar response to rate: HyCLASS 970 produced its lowest yields at the lowest planting rate, while HyCLASS 930 produced its highest yields at this rate (Figure 3.4). There were also differences in yield by row spacing in Perry ($P < 0.0001$). Planting on 19 and 38 cm row spacings resulted in an average of 15% higher yields than those planted on wider 76 cm row spacings (Table 3.4). In Perry, HyCLASS 970 yielded, on average, 320 kg ha^{-1} greater than HyCLASS 930.

3.3.3. Yield Components

At College Station there was an interaction between cultivar and row spacing for pods per plant (Table 3.3). HyCLASS 970 and 930 exhibited opposite trends in pod number in response to row spacing (Figure 3.4). HyCLASS 970 produced the most pods plant^{-1} at the 38 cm row spacing and the fewest at 76 cm, while HyCLASS 930 produced the most pods plant^{-1} at 76 cm and the fewest at 38 cm. At both locations, HyCLASS 970 produced a greater number of pods plant^{-1} than HyCLASS 930. The effect of planting rate on pods plant^{-1} was significant ($P <$ 0.0001), with the number of pods plant^{-1} highest at the lowest planting rate. While there was no difference in pods plant^{-1} between the 3.4 and 5.0 kg ha^{-1} planting rates at College Station, a planting rate of 5.0 kg ha^{-1} in Perry produced fewer pods plant^{-1} than when planted at 3.4 kg ha^{-1} (Table 3.4).

No cultivar difference was observed in College Station for seeds pod^{-1}, but HyCLASS 930 produced an estimated two more seeds per pod than HyCLASS 970 at Perry. Neither planting rate nor row spacing had an effect on seeds per pod at either location. The two locations had similar trends in seeds plant^{-1}. HyCLASS 970 produced more seeds plant^{-1} than HyCLASS 930, and the lowest planting rate produced the most seeds plant^{-1}, with no difference between the 3.4 and 5.0 kg ha^{-1} rates. Row spacing had no effect.

Individual seed weight was greater for HyCLASS 970 than for HyCLASS 930 at both locations by 0.28 mg in College Station and 0.57 mg in Perry (Tables 3.3 and 3.4). As with seeds per pod, neither planting rate or row spacing had an effect on individual seed weight at either location.

3.3.4. Oil Content & Productivity

Oil content was 3.1% higher in HyCLASS 930 than HyCLASS 970 at both locations (Table 3.3 and 3.4). Planting rate influenced oil content at College Station ($P < 0.0002$), with higher oil contents at the highest planting rate (5.0 kg ha^{-1}) compared to the lowest planting rate (1.7 kg ha^{-1}) (Table 3.3). Row spacing had no influence on oil content at either location.

At Perry there was an interaction between cultivar and planting rate for oil productivity (Table 3.4). HyCLASS 930 and 970 exhibited opposite trends in oil productivity in response to planting rate. Oil productivity increased with increasing planting rate in HyCLASS 970, but decreased with increasing planting rate in HyCLASS 930. Row spacing had an influence on oil productivity at Perry, which was reflective of yield differences. Planting on 19 and 38 cm row spacings resulted in higher oil productivity, an average of 15%, than planting on wider 76 cm row spacings. Oil productivity was 26% and 19% higher for HyCLASS 970 than HyCLASS 930 at both College Station and Perry, respectively.

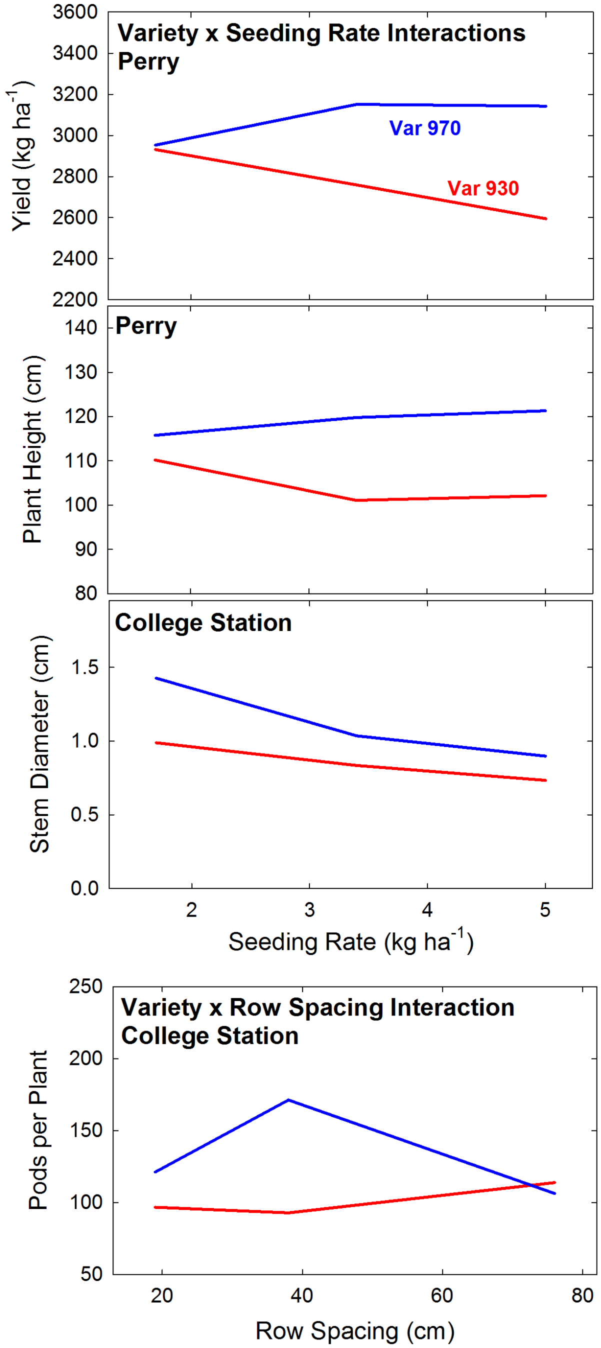

Figure 3.4 Graphical summary of significant interactions at both locations.

Table 3.3 Summary of yield and yield component data from College Station. P-values are included in parentheses. Values for a given treatment factor and response variable followed by the same letter are not significantly different.

Effect	Yield (kg ha^{-1})	Pods Plant^{-1}	Seeds Pod^{-1}	Seeds Plant^{-1}	Seeds ha^{-1}	Seed Weight (mg)	Oil Content (%)	Oil Productivity (kg oil ha^{-1})
Cultivar								
HyCLASS 930	1084 b*	101.2 b	23.5 a	1162 b	4.60 x 10^8 a	2.37 b	48.8 a	22.2 b
HyCLASS 970	1278 a	132.9 a	23.0 a	1558 a	4.86 x 10^8 a	2.65 a	45.7 b	28.0 a
$P < 0.05$	(<0.0001)	(0.005)	(0.569)	(0.007)	(0.194)	(0.0002)	(<0.0001)	(<0.0001)
Rate (kg ha^{-1})								
1.7	1178 a	177.9 a	23.8 a	2113 a	4.69 x 10^8 a	2.53 a	46.5 b	25.4 a
3.4	1191 a	92.0 b	23.8 a	1147 b	4.84 x 10^8 a	2.53 a	47.3 ab	25.3 a
5.0	1174 a	81.3 b	22.1 a	820 b	4.67 x 10^8 a	2.47 a	48.0 a	24.6 a
$P < 0.05$	(0.936)	(<0.0001)	(0.306)	(<0.0001)	(0.738)	(0.705)	(0.0002)	(0.679)
Spacing (cm)								
19	1182 a	109.0 a	22.4 a	1257 a	4.81 x 10^8 a	2.47 a	47.5 a	25.0 a
38	1232 a	132.1 a	23.1 a	1294 a	4.78 x 10^8 a	2.59 a	47.2 a	26.2 a
76	1129 a	110.1 a	24.2 a	1529 a	4.61 x 10^8 a	2.46 a	47.1 a	24.1 a
$P < 0.05$	(0.113)	(0.152)	(0.324)	(0.229)	(0.662)	(0.214)	(0.379)	(0.120)
Cultivar×Spacing	(0.175)	(0.008)	(0.703)	(0.706)	(0.809)	(0.051)	(0.637)	(0.145)
Cultivar×Rate	(0.602)	(0.955)	(0.704)	(0.538)	(0.581)	(0.691)	(0.261)	(0.513)
Spacing×Rate	(0.142)	(0.943)	(0.492)	(0.575)	(0.171)	(0.182)	(0.279)	(0.122)

*Values for a given treatment factor and response variable followed by the same letter are not significantly different at $P > 0.05$.

Table 3.4 Summary of yield and yield component data from Perry. P-values are included in parentheses. Values for a given treatment factor and response variable followed by the same letter are not significantly different.

Effect	Yield (kg ha^{-1})	Pods $Plant^{-1}$	Seeds Pod^{-1}	Seeds $Plant^{-1}$	Seeds ha-1	Seed Weight (mg)	Oil Content (%)	Oil Productivity (kg oil ha^{-1})
Cultivar								
HyCLASS 930	2762 b*	183.0 b	23.0 a	1972 b	1.07×10^9 a	2.61 b	47.8 a	57.8 b
HyCLASS 970	3082 a	221.1 a	21.4 b	2785 a	9.73×10^8 b	3.18 a	44.7 b	68.9 a
P < 0.05	(0.0001)	(0.001)	(0.001)	(0.0001)	(0.009)	(<0.0001)	(<0.0001)	(<0.0001)
Rate (kg ha^{-1})								
1.7	2942 a	241.8 a	22.3 a	3435 a	1.02×10^9 a	2.91 a	46.3 a	63.6 a
3.4	2955 a	205.4 b	22.3 a	2077 b	1.02×10^9 a	2.93 a	46.5 a	63.8 a
5.0	2869 a	158.9 c	22.1 a	1624 b	1.02×10^9 a	2.83 a	46.0 a	62.7 a
P < 0.05	(0.602)	(<0.0001)	(0.900)	(<0.0001)	(0.994)	(0.283)	(0.316)	(0.853)
Spacing (cm)								
19	3050 a	211.6 a	21.8 a	2087 a	1.05×10^9 a	2.92 a	46.4 a	65.9 a
38	3075 a	188.3 a	22.3 a	2588 a	1.10×10^9 a	2.83 a	46.4 a	66.5 a
76	2642 b	206.2 a	22.5 a	2461 a	9.09×10^8 b	2.93 a	46.1 a	57.6 b
P < 0.05	(<0.0001)	(0.183)	(0.499)	(0.054)	(0.0002)	(0.231)	(0.522)	(0.0002)
Cultivar×Spacing	(0.590)	(0.085)	(0.088)	(0.990)	(0.768)	(0.605)	(0.703)	(0.747)
Cultivar×Rate	(0.020)	(0.080)	(0.796)	(0.296)	(0.226)	(0.646)	(0.964)	(0.032)
Spacing×Rate	(0.071)	(0.534)	(0.773)	(0.274)	(0.844)	(0.455)	(0.146)	(0.088)

*Values for a given treatment factor and response variable followed by the same letter are not significantly different at *P* > 0.05.

3.3.5. Stem Diameter

Only at the College Station field site, there was an interaction between cultivar and planting rate on stem diameter (Table 3.5; Figure 3.4), due to relatively high stem diameters at the lowest planting rate in HyCLASS 970. Stem diameters were 56% higher at the lowest planting rate compared to the highest rate in HyCLASS 970 and 36% higher in HyCLASS 930 (Figure 3.3). At both locations, cultivar and planting rate individually had effects on stem diameter (P<0.0001). Compared to HyCLASS 930, HyCLASS 970 stem diameters were 29% larger in College Station and 37% cm larger in Perry. Stem diameters were 0.38 and 0.26 cm larger at the lowest planting rate compared to the highest rate at College Station and Perry, respectively.

3.3.6. Plant Height

At College Station there was an interaction between cultivar and row spacing on plant height, due to opposite responses by the two cultivars to the widest row spacing (Table 3.5). For cultivar HyCLASS 970, the widest row spacing (76 cm) resulted in taller plants at maturity, whereas in HyCLASS 930, plants were the shortest at the widest row spacing (Figure 3.3). At Perry there was an interaction between cultivar and planting rate on plant height (Table 3.6; Figure 3.4). Higher planting rates led to taller plants at maturity for HyCLASS 970, whereas plants were the tallest at the lowest planting rate in HyCLASS 930, with insignificant differences in height at the two higher planting rates (Figure 3.3). At both locations, HyCLASS 970 was taller at maturity than HyCLASS 930. In College Station, planting rate also had an impact, with the lowest planting rate producing taller plants than the highest planting rate.

3.3.7. Crown Height

At both locations, HyCLASS 930 had taller crown heights than HyCLASS 970 when measurements were taken in mid-January. Compared to HyCLASS 970, HyCLASS 930 crown heights were 14% taller in College Station and 22% taller in Perry (Tables 3.5 and 3.6). Planting rate and row spacing greatly affected crown height at both locations (P<0.0001). Crown heights were greatest at the highest planting rate and the widest row spacing. There were no differences in crown height between the 1.7 and 3.4 kg ha^{-1} planting rates at College Station or the 19 and 38 cm row spacings at either location.

3.3.8. Plant Population

At both College Station and Perry there was a cultivar by planting rate interaction for the initial plant population due to a larger increase in HyCLASS 930 population between the 1.7 and 3.4 kg ha^{-1} planting rates than between 3.4 and 5.0 kg ha^{-1} rates, compared to a more linear trend in HyCLASS 970. HyCLASS 930 had higher plant populations than HyCLASS 970, both initially and at harvest, due to HyCLASS 930's smaller seed size and the weight-based planting rates used. Though there were no differences in the initial observations, at harvest the 76 cm row spacing had lower plant populations than the 19 cm spacing at both Perry and College Station, suggesting that plants in the wide row spacing thinned in response to crowding within the rows. As expected, plant population increased with increasing planting rate at both locations.

Table 3.5. Growth measurement data from College Station. Plant height, stem diameter, and final plant population were taken at harvest, crown height was taken on January 19, and initial plant population was taken on November 30. P-values are included in parentheses.

Effect	Plant Height (cm)	Stem Diameter (cm)	Crown Height (cm)	Initial Plant Population (Plants m^{-2})	Final Plant Population (Plants m^{-2})
Cultivar					
HyCLASS 930	111.8 b*	0.85 b	3.2 a	55.9 a	48.0 a
HyCLASS 970	118.3 a	1.1 a	2.8 b	39.3 b	38.0 b
$P < 0.05$	(<0.0001)	(<0.0001)	(0.015)	(<0.0001)	(0.0001)
Rate (kg ha^{-1})					
1.7	118.6 a	1.2 a	2.5 b	24.0 c	24.2 c
3.4	115.4 ab	0.93 b	2.9 b	49.5 b	44.8 b
5.0	111.2 b	0.82 c	3.4 a	69.3 a	60.1 a
$P < 0.05$	(0.001)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)
Spacing (cm)					
19	112.8 a	0.99 a	2.5 b	49.9 a	48.7 a
38	116.3 a	1.0 a	2.8 b	47.8 a	42.2 ab
76	116.2 a	0.94 a	3.6 a	45.2 a	38.2 b
$P < 0.05$	(0.088)	(0.174)	(<0.0001)	(0.167)	(0.003)
Cultivar×Spacing	(0.036)	(0.607)	(0.330)	(0.722)	(0.774)
Cultivar×Rate	(0.301)	(0.011)	(0.692)	(0.006)	(0.567)
Spacing×Rate	(0.122)	(0.138)	(0.186)	(0.775)	(0.370)

*Values for a given treatment factor and response variable followed by the same letter are not significantly different at $P > 0.05$.

Table 3.6. Growth measurement data from Perry. Plant height, stem diameter, and final plant population were taken at harvest, crown height was taken on January 18, and initial plant population was taken December 11. P-values are included in parentheses.

Effect	Plant Height (cm)	Stem Diameter (cm)	Crown Height (cm)	Initial Plant Population (Plants m^{-2})	Final Plant Population (Plants m^{-2})
Cultivar					
HyCLASS 930	104.5 b*	0.73 b	3.3 a	66.3 a	61.5 a
HyCLASS 970	119.0 a	1.0 a	2.7 b	40.2 b	39.8 b
	(<0.0001)	(<0.0001)	(0.006)	(<0.0001)	(<0.0001)
Rate (kg ha^{-1})					
1.7	113.0 a	1.0 a	2.2 c	27.8 c	33.0 c
3.4	110.4 a	0.84 b	2.9 b	55.6 b	52.5 b
5.0	111.7 a	0.74 c	3.8 a	76.4 a	66.5 a
	(0.668)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)
Spacing (cm)					
19	112.0 a	0.86 a	2.5 b	54.1 a	58.3 a
38	111.7 a	0.87 a	2.8 b	56.7 a	52.2 a
76	111.4 a	0.86 a	3.6 a	49.0 a	41.5 b
	(0.981)	(0.951)	(0.0001)	(0.058)	(<0.0001)
Cultivar×Spacing	(0.267)	(0.890)	(0.960)	(0.104)	(0.156)
Cultivar×Rate	(0.034)	(0.601)	(0.666)	(0.005)	(0.346)
Spacing×Rate	(0.275)	(0.147)	(0.574)	(0.348)	(0.303)

*Values for a given treatment factor and response variable followed by the same letter are not significantly different at $P > 0.05$.

3.4 Discussion

Several interactions were found among treatment factors, each involving differences in treatment response between the tested cultivars and none of which were consistent between locations (Figure 3.4). A cultivar by planting rate interaction on yield at Perry showed that HyCLASS 930 yields steadily decreased with increasing seed rates, while HyCLASS 970 yields increased slightly. This may represent a physiological difference between the cultivars, but the same trend was not observed in College Station. Cultivar by planting rate interactions on plant height (Perry) and stem diameter (College Station) resulted from minor varietal variations from the overall trends at a single planting rate. A cultivar by row spacing interaction on pods plant^{-1} at College Station was the result of a deviation from the overall trend for HyCLASS 970, with an increase in pods plant^{-1} in the 15 cm row spacing relative to wider spacing treatment, though significant differences within each variety were minimal. Due to the nature of these interactions, discussion focuses on individual treatment effects.

The two tested canola cultivars, HyCLASS 930 and HyCLASS 970, performed very differently, supporting previous studies that have shown the importance of cultivar selection (Harker et al., 2000; Cathcart et al., 2006). Yield and most other parameters were greater in HyCLASS 970, which matured slightly later (5 days), than in HyCLASS 930 at both field sites. One such parameter was individual seed weight, which was higher in the higher-yielding HyCLASS 970 and contributed to the two cultivars' yield differences. The higher plant populations seen in HyCLASS 930 compared to HyCLASS 970 are the result of HyCLASS 930's smaller seed size, as planting was done on a weight basis, and may have contributed to differences seen between the two cultivars in measurements such as crown height.

Yield component measurements gave interesting insights into the mechanisms by which the cultivars differed in seed production. Despite their yield differences, both cultivars produced a similar number of seeds ha^{-1} at College Station. HyCLASS 970 produced more pods plant^{-1}, but HyCLASS 930 tended to produce more seeds pod^{-1}, contributing to the similarity in production of seed ha^{-1}. HyCLASS 970 still produced more seeds plant^{-1}, despite producing fewer seeds pod^{-1}. The similar number of seeds ha^{-1} is also partially the result of HyCLASS 930's higher plant populations compared to HyCLASS 970.

At both locations, the higher yielding HyCLASS 970 was taller at maturity than HyCLASS 930. Plant height can be an indicator of agronomic performance, used to predict yield in a variety of crops. Assefa et al. (2018) showed a positive correlation between plant height and yield in canola. While seed oil content was about 3% higher in HyCLASS 930, the higher oil content was not enough to make up for the lower yields. Despite its lower seed oil content, HyCLASS 970 produced substantially more oil per hectare due to significantly larger yields.

Planting rate impacted growth measurements such as stem diameter, pods per plant, and, at College Station, plant height. Interestingly, planting rate did not interact with row spacing. The greater number of pods per plant observed at the lowest tested planting rate at both locations supports previous research that shows increased branching and crop adaptability in canola at low plant population densities (Angadi et al., 2003). Planting rate and stem diameter had a negative relationship, which can affect the crop's lodging potential, though no lodging was observed in this study. Wu and Ma (2016) showed that canola cultivars bred for lodging resistance had greater stem diameters than more susceptible cultivars. The commonly recommended planting rate for canola is 5.6 kg ha^{-1} (Brown et al., 2008; Canola Council, 2017d). This recommendation is based on an estimated seedling survival of 50-60% (Canola Council, 2017d). In the South, however, where winter kill is less of an issue, seedling survival may be higher. Seedling survival at College Station and Perry, where seeds were planted into sufficient moisture and no winter kill was observed, was 89 and 90%, respectively. The lack of difference in yield among the three planting rates tested suggests that planting rates can be dropped as low as 1.7 kg ha^{-1} in this region. Morrison et al. (1990) planted summer canola in Manitoba and similarly found that yields could be maximized at planting rates of 1.5 and 3.0 kg ha^{-1}. With canola seed costs estimated to be around \$20.25 kg^{-1} in 2018 (Manitoba Agriculture Farm Management, 2018), dropping planting rates from 5.6 kg ha^{-1} to 1.7 kg ha^{-1} would save producers over \$75 ha^{-1}.

Unlike planting rate, row spacing impacted seed yield, but had no impact on growth parameters like plant height and stem diameter. Yield was reduced by 15% at the widest row spacing tested (76 cm), but only in the higher yielding environment (Perry). Wysocki and Sirovatka (2009) reported similar results of inconsistently lower yields with 76 cm row spacings. There is little other data available in the literature on relatively wide row spacings in canola, so this finding helps to establish the risk associated with planting on rows as wide as 76 cm. The similarity in yield between the 19 and 38 cm row spacings in this study is supported by data from multiple studies reporting minimal differences in yield between 15 and 38 cm row spacings (Xie et al., 1998; Johnson and Hanson, 2003).

Planting rate and row spacing had pronounced effects on crown height, which increased with increasing planting rate and row spacing. While higher crown heights are often associated with decreased winter survival (Holman et al., 2011), no freeze damage was observed at either location in this study, despite the occurrence of freezing conditions. The two tested cultivars also differed in crown height. In this case, the difference between the two cultivars may be the result of vigorous fall growth in HyCLASS 930, which also had higher plant heights than HyCLASS 970 at the time crown height measurements were taken. Increasing crown heights with increasing planting rate and row spacing also suggests that crown heights increase in response to increasing inter-plant competition. This may become more important as production is pushed farther north and winter survival becomes more of a concern, as Showalter (2017) showed a negative correlation between plant density and winter survival, reinforcing the idea that greater competition among plants within a row increases the risk of winter kill.

The average yield obtained at Perry, 2787 kg ha^{-1}, is similar to the 2500 kg ha^{-1} average canola yield in Manitoba for 2017 and just higher than Canada's overall yield average of 2300 kg ha^{-1} (Canola Council, 2017c). The average yield at College Station, 1181 kg ha^{-1}, was lower than the United States' overall yield average of 1746 kg ha^{-1} for 2017 (USDA NASS, 2018). Fall-planted spring canola provides producers in the Southern U.S. with a system for growing canola that circumvents high summer temperatures and takes advantage of typical warmer winters. The flexibility in row spacing found in this study will enable most new canola producers to use their existing, narrowly spaced drills for planting, but indicates that relatively wide spaced planters should not be used. The ability to plant below the commonly recommended planting rate will help to decrease input costs by over \$75 ha^{-1} and may entice more producers to incorporate canola into their existing winter cropping systems.

4. RESIDUAL CHEMICAL EFFECTS OF WHEAT CHAFF ON CANOLA GERMINATION AND EARLY GROWTH

4.1 Introduction and Objectives

The residual effects of wheat have been widely studied for their potential to impact the germination and growth of other plants. These residual effects encompass a wide range of possible physical and chemical effects, including effects on available soil moisture and light interception, as well as microbial activity and allelopathy. The potential effects of wheat residue on subsequent crops, soil health, and pest prevalence can be both positive and negative, as shown in studies on the effect of wheat on crops such as maize (*Zea mays*), Austrian winter peas (*Pisum sativum*), and cotton (Opoku et al., 1997; Huggins and Pan, 1990; Hicks et al., 1989). But the effects of wheat on canola, a crop increasingly rotated with wheat, have been less widely studied.

An Australian study looked at the effects of aqueous extracts of undecomposed wheat residue on canola germination and radicle elongation, and while results were variable, differences were observed in both wheat phytotoxicity and canola susceptibility, suggesting that the effects of allelopathy may be cultivar-dependent (Bruce et al., 1999). Bruce et al. (2005) found that larger wheat stubble loads had greater negative effects on emergence and growth of canola than lower stubble loads, suggesting that areas with greater wheat growth would be more vulnerable to negative residual effects on canola. In that study, it was unclear whether the reported effects were biochemical or physical effects of wheat. Bruce et al. (2006b) suggested that poor growth of canola planted into wheat stubble may be caused by physical, rather than biochemical, factors and could potentially be remediated by clearing stubble away from emerging canola seedlings. This study also observed slower emergence and elongated stems in canola planted into stubble, which is thought to be due to shading by the stubble that reduces the amount of photosynthetically active radiation and the red to far-red ratio of light reaching the emerging seedling.

Wheat can have a number of other residual effects as well, both beneficial and negative. Wheat stubble can intercept applied herbicides, potentially reducing the efficacy of preemergence weed control (Ghadiri et al., 1984). Wheat residue extracts have been shown to inhibit root growth in ragweed and pitted morning glory (Liebl and Worsham, 1983) and the same impact may be observed on crop plants. Effects of decomposing wheat residue on soil pH seem to be minimal (Xu and Coventry, 2003), but decomposing wheat straw has been shown to impact both the size and composition of microbial communities, which may help to increase soil organic matter content in the long-term (Bastian et al., 2009; Ocio et al., 1991). Additionally, Zavalloni et al. (2011) showed that soils treated with wheat straw had higher microbial C and N levels and lower soluble organic N than untreated soils, effectively decreasing the leaching potential of nitrogen in the soil.

The potential for residual chemical effects of wheat to affect germination and growth of canola need to be better understood as canola production expands in wheat production areas of the United States, including wheat systems in the Southern Great Plains region. Further research and data are needed to determine if wheat cultivars bred for and grown in the Southern Great Plains may have an influence on emergence and growth of a subsequent canola crop. Two studies were conducted to evaluate this concern. The objective of the first study was to determine the direct impact of wheat stubble on canola germination under laboratory conditions. The objective of the second study was to determine the effects of wheat stubble, including 15 varieties of wheat replicated from two sources, on canola germination and early growth in two soils in an outdoor pot study.

4.2 Materials and Methods

4.2.1. Laboratory Evaluation

A laboratory test was carried out to evaluate the direct effects of wheat chaff on canola, through the evaluation of canola germination and radicle extension after exposure to aqueous wheat chaff extracts. In preparation for making chaff extracts, the wheat chaff was first ground to pass a 2 mm sieve. Sterile vials were loaded with ground chaff from the wheat cultivar 'Gallagher' and distilled water at concentrations of 0, 5, 25, 50, 75, and 100 g L^{-1}. Gallagher was obtained from 2017 Uniform Wheat Variety Trial conducted in Texas A&M AgriLife Research Station at Chillicothe, TX. The vials were kept at 25° for 24 hours, then extract solutions were isolated by passing the mixture through a 0.25 mm screen. Canola seeds (HyClass 225W) were washed two times by adding the seeds to distilled water in a sterile, sealable container and shaking to remove seed treatment and any other chemical residues that may have interacted with treatment factors. Canola seeds were soaked in respective extract solutions for three hours (Siddiqui et al., 2009). Germination paper was placed in petri dishes (100 mm x 15 mm) and wetted with 6 mL of extract solution. Twenty treated seeds were placed in petri dishes corresponding with extract solution, with four replications in a completely randomized factorial design. The tests were conducted in a dark lab at an ambient temperature of approximately 25°C. Germination and radicle elongation rates were monitored on all seeds daily for four days using digital calipers (VWR Traceable Digital Calipers), with germination defined as radicle extension of at least one mm. With visually determined loss of moisture in the dishes, distilled water was added to all dishes uniformly around the edge of the germination paper.

4.2.2. Pot Study

A pot study was conducted outdoors in Vernon, Texas, to evaluate impacts of wheat chaff on germination and early growth of canola. The experimental treatments included two soils, chaff of 15 wheat varieties, plus untreated (no chaff) controls for each soil in a completely randomized full factorial design. The study was repeated with chaff from two locations, or chaff sources (Abilene and Chillicothe). There were three replications per treatment combination, making a total of 186 pots. The two soils used were a Miles loamy fine sand (84% sand, 9% silt, 7% clay) from Lockett, TX (34°05'37.5"N, 99°21'58.1"W) and a Grandfield fine sandy loam (65% sand, 21% silt, 14% clay) from Chillicothe, TX (34°11'43.8"N, 99°31'23.6"W). Soil for the pots, as well as soil samples collected for nutrient analysis, were collected to a depth of 25 cm. Wheat chaff was collected at the time of harvest from Abilene, TX (32°30'14.73"N, 99°38'04.01"W) and Chillicothe, TX (34°11'43.8"N, 99°31'23.6"W) from three replicate field plots per wheat cultivar and thoroughly mixed. The cultivars chosen for evaluation come from a variety of sources and genetic backgrounds, including university and commercial breeding programs from Texas, Oklahoma, and Kansas, and reflect those found on the 2017 Texas A&M AgriLife Wheat Picks List (Neely, 2017), commonly grown cultivars in the Rolling Plains and High Plains of Texas (Neely et al., 2017b) and new cultivars that show good yield and regional adoption potential (Neely et al., 2017b). The following cultivars were used: Bentley, Gallagher, Greer, Jackpot, Long Branch, SY Grit, SY Southwind, T158, TAM 114, TAM 204, TAM 401, WB 4458, WB 4721, WB Cedar, and Zenda.

The study was established on 9 June 2017. Plastic pots, 3.8 liters (one gallon) in volume, were filled with soil, watered, and allowed to settle before adding chaff to the surface of all treatment pots. Screens were placed on the bottom of each pot to allow drainage without soil loss. Each pot was uniformly topped with 9 g of chaff, which was based on a chaff density of 4935 kg ha^{-1} in the field, determined from the average chaff density of samples collected from the Abilene location. The chaff was cut into 2.5 cm long pieces. Netting was placed over each pot to hold the wheat chaff in place, and pots were placed in an outdoor holding area for the summer, largely representative of field conditions. The pots were lightly sprayed with glyphosate (475 mL/9.5 L water) in early July and mid-September to control weeds. In early October, just prior to planting, chaff was removed from the soil surface to eliminate any physical effects of the chaff on canola. Canola seeds were planted in the pots on 5 October 2018, coinciding with typical field planting dates for canola in this region. The hybrid cultivar 'Pioneer 46W94' was used. Sixteen seeds were planted per pot in a grid pattern, with spacing of 2.5 cm. Following planting, pots were then moved to a greenhouse and germination was evaluated and recorded daily from four days after planting and until seven days after planting. Germination was defined as shoot elongation of at least 1 mm above the soil surface. After final germination counts were taken, each pot was thinned to two plants per pot. At 40 days after planting, plants were cut at the soil surface, dried at 80°C for four days, and weighed to assess early growth. During the 40-day growing period, the pots were visually assessed for soil moisture and watered to maintain a moist surface, eliminating the potential for water availability to be a confounding factor in early growth results. No fertilizer was added to the pots.

4.2.3. Statistical Analysis

For the statistical analysis of the laboratory study, SigmaPlot was used for regression analysis to determine trends in germination and radicle elongation in response to varying chaff extract concentrations. For the pot study statistical analysis was conducted using the GLIMMIX procedure in SAS 9.4. In the statistical model, chaff (wheat cultivar) and soil were considered fixed effects, while chaff source was a random effect. CONTRAST statements were used to make orthogonal contrasts to compare each wheat chaff cultivar treatment individually and collectively to the control and to compare the soil type treatments to each other (Appendix A-2 and A-3). All data was checked for compliance with the assumptions of normality and homogeneity of variance. A probability threshold of 0.05 was used to determine statistical differences.

4.3 Results

4.3.1. Laboratory Evaluation

Germination of canola was delayed by wheat chaff extract. After one day of exposure to moisture and chaff extract, the rate of germination was reduced by about 70% with exposure to the highest tested chaff extract concentrations (75 and 100 g L^{-1}) relative to the control (0 g L^{-1}). Although the initial rate of germination was reduced by wheat chaff extract, final germination percentages were minimally affected after four days (Figure 4.1). In contrast, the rate of radicle elongation was negatively affected by wheat chaff in the long run. The results in Figures 4.1 and 4.2 show that the inhibitory effects of the wheat chaff extract increased with increasing concentration. After four days, average radicle length was 45% less with exposure to chaff extract of 100 g L^{-1} relative to the control.

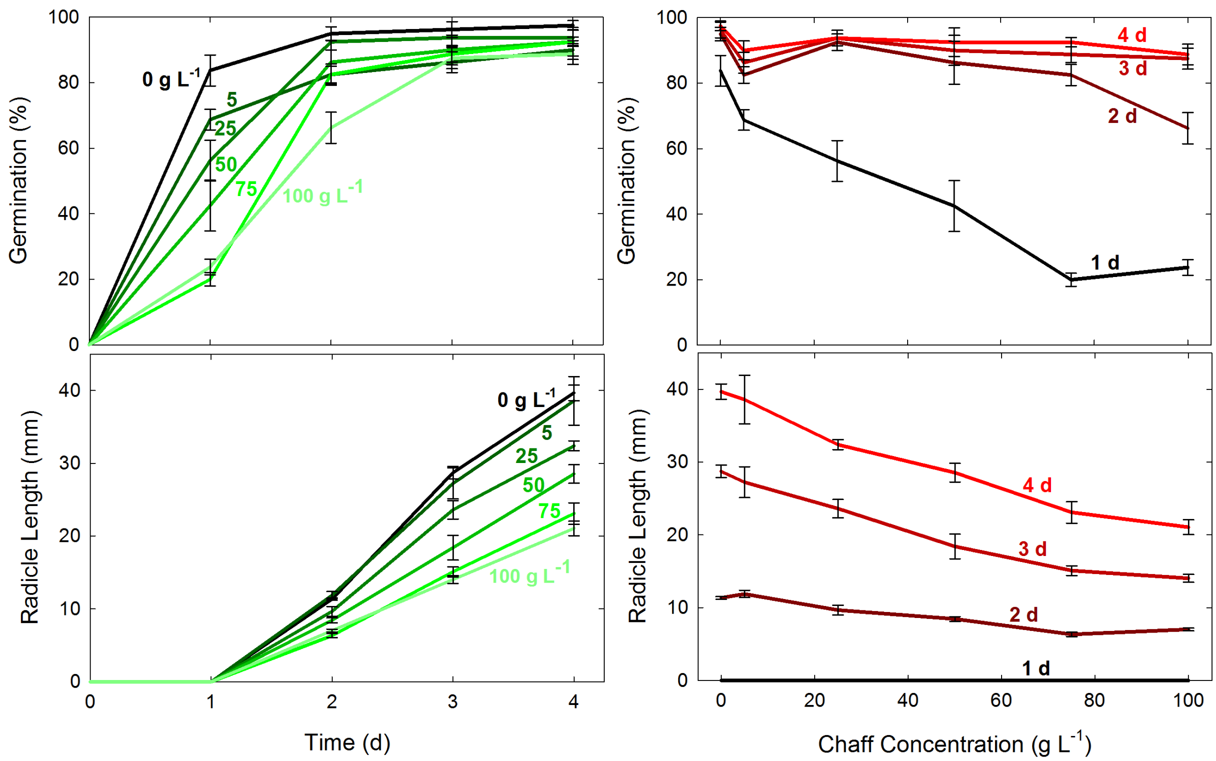

Figure 4.1. Percent germination and radicle length at six chaff concentrations, represented over time (left) by chaff concentration (right). Error bars represent standard error.

Germination was most affected by the chaff extract on day 1 and radicle elongation was most affected on day 4. The relationship between these response variables and chaff concentration on the days they were most affected is shown in Figure 4.2. Differences in germination were observed most strongly at day 1, but the differences narrowed over time with ultimately no difference seen on day 4. Radicle elongation, however, showed no differences in response to chaff extract concentration at day 1, with differences between treatments increasing over time.

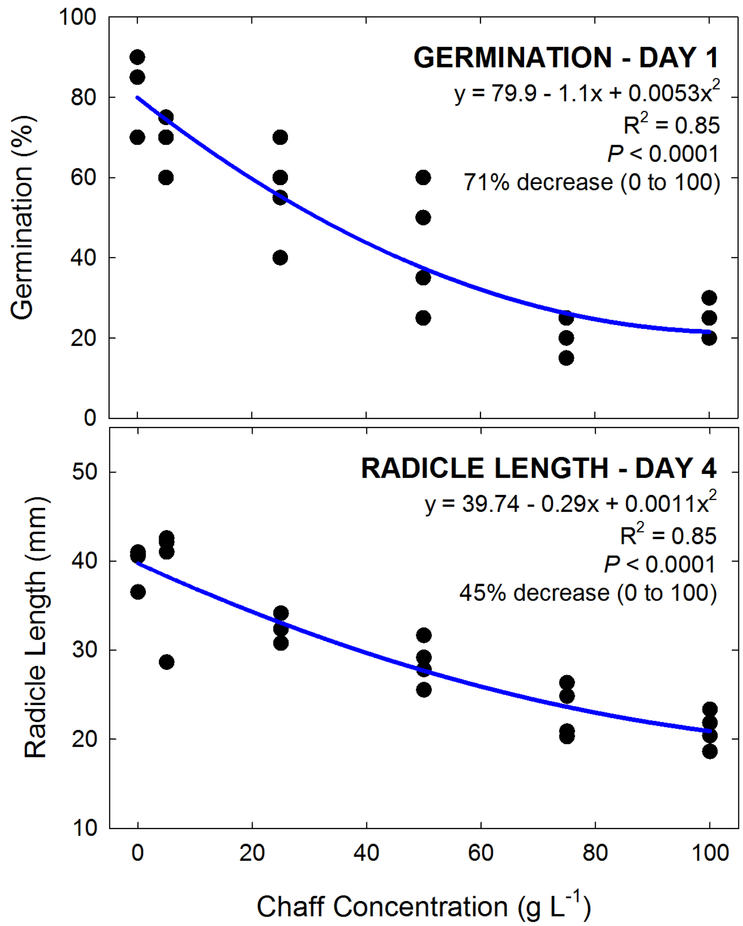

Figure 4.2. Regression of germination and radicle length in response to chaff concentration at times when impacts were most severe.

4.3.2. Pot Study

Temperature and precipitation data for the period of the pot study during which pots were placed outside are shown in Figures 4.3 and 4.4. Temperatures were average for the time of year and rainfall was generally average, which the exception of September, during which rainfall was above average.

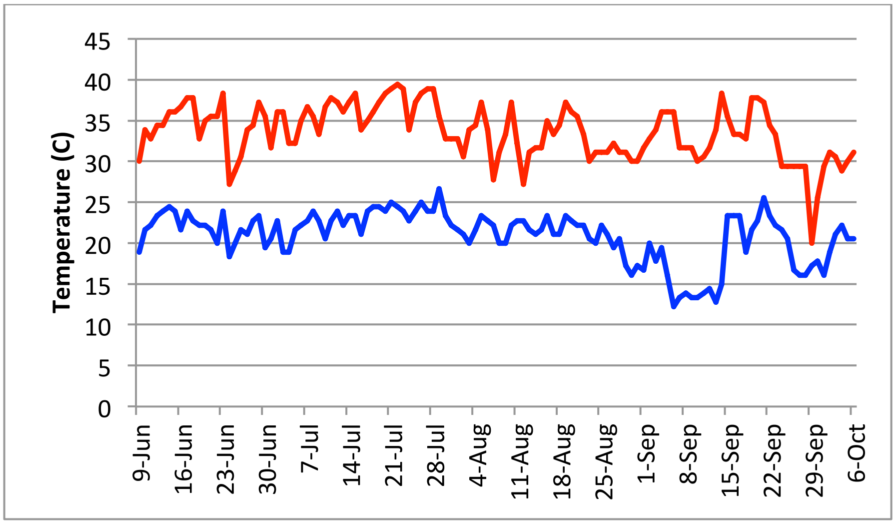

Figure 4.3 High and low temperatures in Vernon, TX over the period of the pot study during which pots were placed outside. (National Weather Service, 2018)

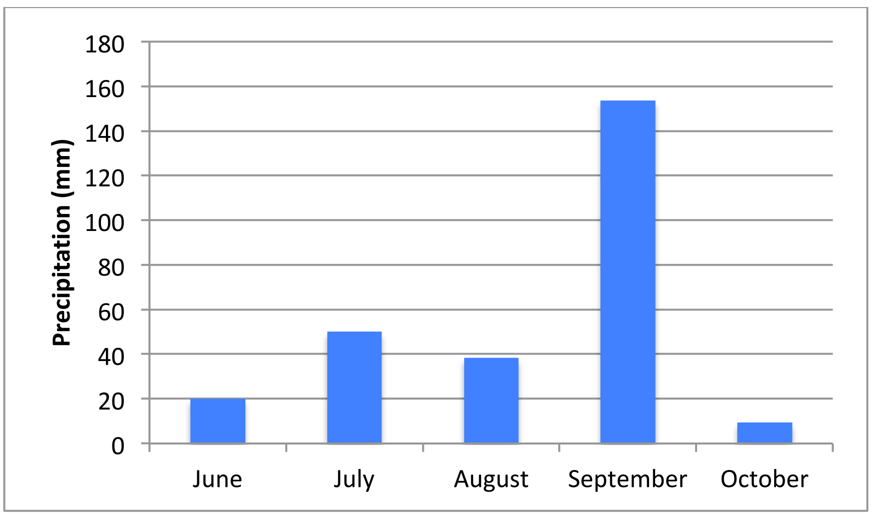

Figure 4.4 Precipitation for Vernon, TX over the period of the pot study during which pots were placed outside. (National Weather Service, 2018).

Soil test results show that both soil types were low in nitrogen and slightly low in phosphorus, based on the Texas A&M University Soil Testing Laboratory's recommendations for canola (Table 4.1).

Table 4.1. Nutrient and pH analysis of the two soil types. All nutrient amounts are in ppm.

	Chillicothe fine sandy loam	Lockett loamy fine sand
pH	7.80	7.95
NO_3-N	2.37	5.00
NH_4-N	3.39	2.97
Phosphorus	48.0	31.0
Potassium	379	192
Magnesium	160	158
Calcium	2560	853
Sulfur	7.00	28.0
Boron	0.60	0.40
Zinc	2.05	1.95
Iron	39.0	71.0
Manganese	166	57.0
Copper	2.35	1.10

Nutrient content and pH of the wheat chaff extract was analyzed and the results are summarized in Table 4.2. The extract from the two wheat chaff sources had generally similar nutrient contents and pH.

Table 4.2. Nutrient and pH analysis of Gallagher wheat chaff extract (50 g L^{-1}) from both chaff sources, Chillicothe and Abilene. All nutrient amounts are in ppm.

	Wheat Chaff Extract (Chillicothe)	Wheat Chaff Extract (Abilene)
pH	5.20	5.70
Nitrate N	40.4	36.6
Phosphorus	33.9	11.6
Potassium	450	369
Magnesium	35.8	30.8
Calcium	56.9	51.3
Sodium	2.41	7.94
Boron	0.07	0.16
Iron	0.61	0.94
Manganese	0.97	1.52
Sulfate	134	86.4

Overall, wheat chaff had no effect on germination of canola (Table 4.3), with no differences between two soil types (Table 4.4). Germination was lower than that of the control with application of chaff from only one wheat cultivar, with 87.5% germination compared to 96.9%. Early growth of canola, however, was affected by wheat chaff. Dry matter biomass was greater than the control following soil cover with 13 of the 15 wheat chaff cultivars tested (Table 4.3). The average biomass of canola (40 days of growth) planted in soil with chaff was 2.87 g $plant^{-1}$ compared to 2.33 g $plant^{-1}$ for the control pots, a 23% increase. Soil type also had an impact on early growth. Plants had a higher biomass in the fine sandy loam soil compared to those planted in the loamy fine sand soil (Table 4.4). Those planted in the fine sandy loam had an average biomass of 0.68 g $plant^{-1}$ greater than those planted in the loamy fine sand.

Table 4.3. Germination and early biomass production of canola planted into pots treated with chaff of 15 wheat cultivars with comparisons to the control (no chaff treatment). Results are averaged between tests in two soils and with chaff from two sources.

Cultivar	Germination		Early Growth Biomass	
	Value (%)	*P*-Value vs Control	Biomass (g plant^{-1})	*P*-Value vs Control
Control	96.9	-	2.33	-
Bentley	93.2	0.2997	2.98	0.0017
Gallagher	92.7	0.2399	2.69	0.0756
Greer	96.9	1.0000	2.78	0.0266
Jackpot	96.5	0.9083	2.83	0.0142
Long Branch	95.8	0.7608	2.85	0.0114
SY Grit	91.7	0.1498	2.74	0.0436
SY Southwind	93.8	0.3704	3.03	0.0009
T158	95.8	0.7608	2.92	0.0045
TAM 114	93.2	0.2997	2.93	0.0035
TAM 204	95.9	0.7799	2.88	0.0072
TAM 401	87.5	0.0196	2.68	0.0824
WB 4458	92.7	0.2399	2.90	0.0057
WB 4721	94.4	0.4840	2.93	0.0040
WB Cedar	94.8	0.5456	3.07	0.0004
Zenda	96.4	0.8788	2.81	0.0195
All Cultivars	94.1	0.3783	2.87	0.0025

Table 4.4. Germination and early biomass production of canola planted in the sandy loam (Chillicothe) and loamy sand (Lockett) soils and contrasts between the treatment and control pots.

	Germination (%)	**Biomass (g plant^{-1})**
Sandy Loam Control	97.9	2.62
Sandy Loam Treatment	93.7	3.21
Loamy Sand Control	95.8	2.05
Loamy Sand Treatment	94.5	2.52
	Contrasts	
	Germination *P*-Value	**Biomass *P*-Value**
Sandy Loam Control vs. Treatment	0.299	0.012
Loamy Sand Control vs. Treatment	0.742	0.044
Sandy Loam Control vs. Loamy Sand Control	0.667	0.078
Sandy Loam Treatment vs. Loamy Sand Treatment	0.377	<0.0001

4.4 Discussion

In the laboratory study, though canola germination was unaffected in the long run, prolonged decreases in the rate of radicle elongation indicate that wheat chaff can negatively affect canola seedlings, and the impacts increase with increasing chaff concentration. If this were realized in the field, decreased radicle elongation could delay crop emergence, lead to poor seedling growth, and/or high seedling mortality. Bruce et al. (1999) found similar results in the lab, in which wheat leachates had no effect on final germination percentage of canola, but the rate of radicle elongation was reduced. These results demonstrate the negative impacts wheat chaff can have on canola, though these effects are not likely expected under field conditions, as explored further in this section.

In the pot study conducted outdoors, in which wheat chaff was placed on the soil surface during the summer fallow period but removed prior to planting canola, treatment with wheat chaff did not affect canola emergence. In this study, chaff was removed from the soil surface just before planting to isolate any observed treatment effects to residual chemical effects (not physical). The lack of negative impacts on canola germination in this test substantiates the conclusion of the study reported by Bruce et al. (2006b), which found that the negative impacts on germination due to wheat chaff in their study were likely physical rather than chemical impacts, as a plastic mulch treatment produced similar results to the wheat stubble treatments. In this case, moving stubble out of the seed row at the time of planting would be sufficient to avoid any canola emergence issues due to wheat stubble.

No major differences were observed in the effect of chaff on germination among the 15 cultivars tested, with the exception of one wheat cultivar contributing to slightly lower canola germination rates. This is in contrast with the findings of Bruce et al. (1999) who tested impacts of two wheat cultivars on two canola cultivars and found cultivar interactions, in both wheat phytotoxicity and canola sensitivity. Studies have shown similar cultivar-specific interactions in other crops. For example, differences in allelopathic or biochemical impacts of different wheat cultivars have been observed on annual ryegrass root length (Wu et al., 2003) and germination of several weed species (Steinsiek et al., 1982).

A lack of observation of inhibitory chemical effects of wheat chaff on germination of canola, in this study and others, may be due to at least two factors: degradation of the wheat chaff's allelopathic chemicals during the summer fallow period and soil moisture dynamics during the moisture imbibition and germination processes of canola seeds. Several studies have reported a reduction in phytotoxicity as wheat straw decomposes (Guenzi et al., 1967; Kimber, 1967; Wu et al., 2001). Residual chemicals lose their phytotoxicity as they undergo a number of processes, such as leaching, microbial degradation, and soil adsorption (Wu et al., 2001).

Phytochemicals in the wheat chaff in this study may have degraded or leached out of the soil over the summer, reducing or eliminating any impacts to the canola planted in the fall. The lack of negative impacts may also be due to moisture dynamics. When planted into an unsaturated soil, seeds imbibe water primarily as vapor to carry out the germination process (Wuest, 2007). In this case, any allelochemicals dissolved in liquid water would either not be imbibed by the seed or taken up only in small quantities. Only in relatively wet soils would seeds be likely to imbibe enough liquid water—and dissolved chaff allelochemicals, if present—to have a significant impact on germination and radicle elongation, experiencing effects similar to those seen in the laboratory.

There are several possible explanations for why canola planted into soil following cover with wheat chaff had greater early growth than with no chaff. Chaff extracts, derived from short-term incubation in the lab, contained around 40 ppm nitrate N (Table 4) or 0.8 mg N per gram of chaff, suggesting that the chaff could have contributed at least 7.2 mg N to each pot. Based on a biomass productivity of 3 g per pot and an estimated 3% N content of the biomass, 8% of the treatment plants' total N may have been derived from the chaff, while this nutrient source was absent in the control. The estimate of 8% may be low, since the lab extracts were derived from short-term incubation, as opposed to the summer-long incubation of chaff in the pots, but may also be high, due to N losses over the summer or other N recovery issues. Chaff-derived nutrients other than N, such as S and P, may have had an impact on early growth as well. Another possible explanation is that the decomposing chaff may have helped to lower the soil pH, making micronutrients like zinc and boron more available (Bolan et al., 2003). Retained stubble on the soil surface has been shown to help maintain soil moisture (Dao, 1993), improving soil moisture available to subsequent crops, but chaff was removed prior planting canola in this study and the pots were all watered adequately during the project period to eliminate moisture-related differences between the control and treatment pots.

The results of these two studies indicate that while the chemical properties of wheat chaff have the potential to negatively impact canola germination and seedling growth, these inhibitory effects are not expected under typical field conditions. The results indicate that positive, growth promoting residual impacts of wheat chaff may be observed in practice.

5. CONCLUSIONS

In order for the U.S. to become more self-sufficient in canola production and reduce dependence on imports, production of the crop will need to expand to new areas. Texas and the southern U.S. present an opportunity for canola acreage expansion, as agricultural producers in the region have limited winter crop rotation options. The climate of the region is dynamic, transitioning from more temperate to sub-tropical going southward. Warm winters create a roadblock to successful winter canola production due to lack of vernalization in more southerly locations, while winter canola production is possible in more northerly parts of the region. In the deep South, perhaps the best option for producers is fall-planted spring canola. Research and data on the best agronomic practices for canola in this region have been needed to increase producer interest and encourage adoption. Across the South, but especially in northerly parts of the region, canola may best fit into existing wheat cropping systems, and there have been concerns about potential allelopathic impacts of wheat residue on canola. Research has been needed to evaluate potential impacts.

To better establish fall-planted spring canola in South Texas, a field study was conducted at two locations to determine optimal optimal row spacing and planting rate to maximize yields. While no differences were seen at one location, the decreased yields observed at the wide 76 cm row spacing at Perry indicates there is risk in planting on wide spacings. This widest row spacing also lead to increased crown heights and decreased stem diameters, which could affect winter hardiness and lodging potential as production is pushed further north of these two trial locations. There were no differences in yield among the three tested planting rates (1.7, 3.4, and 5.0 kg ha^{-1}), suggesting that planting rates can be dropped lower than the current general recommendation of 5.6 kg ha^{-1}. Dropping planting rates from 5.6 to 1.7 kg ha-1 could save producers over \$75 ha^{-1} in seed costs. Though both locations experienced a colder than normal winter, no frost damage was observed at either location, which suggests that winter-kill and frost damage may not be a major concern for producers considering fall-planted spring canola in this area. But while both environments proved favorable for canola production, one cultivar out-performed the other, highlighting the importance of cultivar selection.

To address concerns about allelopathic impacts of wheat residue on emergence and early growth of canola, a laboratory evaluation and a pot study were conducted. These studies showed that the potential of wheat to affect canola may be conditional. Soaking canola seeds in wheat chaff extract had a negative impact on canola radicle elongation in the lab, revealing a worst-case scenario. But a lack of inhibitory effects on canola grown in pots treated with wheat chaff suggest that chemical effects of wheat likely will not have negative chemical impacts on canola under typical field conditions. In contrast, the results of the study showed positive impacts of wheat chaff on early canola growth. Though wheat chaff may not pose a chemical risk to successful canola production, data reported in the literature shows it is possible that wheat stubble may have negative physical effects on canola emergence, making residue management important if planting canola into a no-till wheat systems.

These findings show that canola has the potential to be a profitable alternative winter crop for agricultural producers in Texas and the broader southern region. With a high demand for canola products in the U.S. and a crushing facility located in Texas, producers have access to a strong market and limited transportation costs. Furthermore, agricultural producers who produce wheat—the most common winter crop in the region—can use the same equipment for canola, eliminating additional overhead equipment costs. Though canola is currently a minor crop in

Texas, high demand for canola oil, interest in canola meal for livestock production, and the benefits of rotating canola into a wheat system may lead to opportunities for acreage expansion in the future.

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APPENDIX

A-1: PROC GLIMMIX procedure for statistical analysis of growth measurements and yield component data.

```
PROC GLIMMIX data=canola;
CLASS Block Variety Spacing Rate;
MODEL {insert response variable} = Variety | Spacing | Rate;
RANDOM Block;
LSMEANS Variety | Spacing | Rate/pdiff lines adjust=tukey;
RUN;
```

A-2: PROC GLIMMIX procedure for statistical analysis and wheat chaff variety comparisons.

```
PROC GLIMMIX DATA=pots PLOTS= Studentpanel(BLUP) nobound;
      CLASS Soil Variety Chaff;
      MODEL Biomass = Soil Variety/ddfm=kr;
      RANDOM Chaff;
      LSMEANS Soil Variety/lines adj=TUKEY;
      CONTRAST 'V1 vs control' Variety -1 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0;
      CONTRAST 'V2 vs control' Variety 0 -1 0 0 0 1 0 0 0 0 0 0 0 0 0 0;
      CONTRAST 'V3 vs control' Variety 0 0 -1 0 0 1 0 0 0 0 0 0 0 0 0 0;
      CONTRAST 'V4 vs control' Variety 0 0 0 -1 0 1 0 0 0 0 0 0 0 0 0 0;
      CONTRAST 'V5 vs control' Variety 0 0 0 0 -1 1 0 0 0 0 0 0 0 0 0 0;
      CONTRAST 'V7 vs control' Variety 0 0 0 0 0 1 -1 0 0 0 0 0 0 0 0 0;
      CONTRAST 'V8 vs control' Variety 0 0 0 0 0 1 0 -1 0 0 0 0 0 0 0 0;
      CONTRAST 'V9 vs control' Variety 0 0 0 0 0 1 0 0 -1 0 0 0 0 0 0 0;
      CONTRAST 'V10 vs control' Variety 0 0 0 0 0 1 0 0 0 -1 0 0 0 0 0 0;
      CONTRAST 'V11 vs control' Variety 0 0 0 0 0 1 0 0 0 0 -1 0 0 0 0 0;
      CONTRAST 'V12 vs control' Variety 0 0 0 0 0 1 0 0 0 0 0 -1 0 0 0 0;
      CONTRAST 'V13 vs control' Variety 0 0 0 0 0 1 0 0 0 0 0 0 -1 0 0 0;
      CONTRAST 'V14 vs control' Variety 0 0 0 0 0 1 0 0 0 0 0 0 0 -1 0 0;
      CONTRAST 'V15 vs control' Variety 0 0 0 0 0 1 0 0 0 0 0 0 0 0 -1 0;
      CONTRAST 'V16 vs control' Variety 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 -1;
      CONTRAST 'All Vs vs control' Variety -1 -1 -1 -1 -1 15 -1 -1 -1 -1 -1 -
1 -1 -1 -1 -1;
      OUTPUT out=new pred=pred stderr=sepred resid=resid student=student;
RUN;
PROC UNIVARIATE DATA=pots NORMAL PLOT;
      BY Soil Variety;
      VAR Biomass;
      HISTOGRAM Biomass;
      QQPLOT Biomass/NORMAL (MU=EST SIGMA=EST COLOR=RED L=1);
RUN;
ODS RTF CLOSE;
RUN;
```

A-3: PROC GLIMMIX procedure for statistical analysis and soil type comparisons.

```
PROC GLIMMIX DATA=soil PLOTS= Studentpanel(BLUP) nobound;
      CLASS Soil Variety Chaff;
```

```
      MODEL Biomass = Soil Variety/ddfm=kr;
      RANDOM Chaff;
      LSMEANS Soil Variety/lines adj=TUKEY;
      CONTRAST 'sandy loam control vs sandy loam treatment' Soil -1 1 0 0;
      CONTRAST 'loamy sand control vs loamy sand treatment' Soil 0 0 -1 1;
      CONTRAST 'sandy loam control vs loamy sand control' Soil -1 0 1 0;
      CONTRAST 'sandy loam treatment vs loamy sand treatment' Soil 0 -1 0 1;
      OUTPUT out=new pred=pred stderr=sepred resid=resid student=student;
RUN;
PROC UNIVARIATE DATA=soil NORMAL PLOT;
      BY Soil Variety;
      VAR Biomass;
      HISTOGRAM Biomass;
      QQPLOT Biomass/NORMAL (MU=EST SIGMA=EST COLOR=RED L=1);
RUN;
ODS RTF CLOSE;
RUN;
```