SIMULATED HAIL DAMAGE ON SPRING CANOLA (BRASSICA NAPUS L.): NON-

UNIFORM STAND REDUCTION AND STEM CUT-OFF

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Title

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota

State University's regulations and meets the accepted standards for the degree of

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ABSTRACT

Hail damage in canola has been characterized with symptoms such as randomly broken stems and loss of plants. The effect on stand reduction and stem cut-off in canola has yet to be addressed. Two separate experiments, stand reduction and stem cut-off, were conducted at six environments using a factorial arrangement, with four growth stages and five levels of intensity as the two factors, and four replications for each treatment. Data on seed yield, seed oil, and seed protein from each plot of five environments, and yield contributing traits from twenty plants per treatment from four environments were taken. Seed yield losses increased as both growth stage and level of stem cut-off/stand reduction increased. A regression equation was developed to estimate the yield reduction resulting from different levels of stand reduction/stem cut-off at four growth stages. Highest seed yield reductions were 82% and 43% at 90% stand reduction/stem cut-off, respectively.

ACKNOWLEDGEMENTS

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1. GENERAL INTRODUCTION

Argentine canola/rapeseed *(Brassica napus* L.) is a common oilseed crop in the Northern Great Plains region of North America. According to the National Agriculture Statistics Service (NASS, 2016), North Dakota is the leading producer of domestically grown canola, and accounted for approximately 86% of all harvested acres in the United States in 2016. Other states that have high acreage of canola include Minnesota, Montana, and South Dakota.

The primary market for canola oilseed is for the edible oil as a result of the high levels of mono- and poly-unsaturated fatty acids, which promotes cardiovascular health. This is due to canola having low levels of saturated and transaturated fats associated with cardiovascular disease such as heart disease. Other markets for canola oilseed include using the high protein meal as animal feed for cattle and poultry, and using the oil for biodiesel production. After soybean (*Glycine max* (L.) Merril) and palm (*Eleais guineensis*) oil, canola is the third largest source of vegetable oil in the global trade.

The word canola is derived from "Canadian Oil Low Acid" due to its low erucic acid content (<2%) and low glucosinolate content (less than 30 micromoles/gram) in the meal. Non-domesticated *Brassica* oil contain high levels of erucic acid and high glucosinolate in the meal. High erucic acid consumption is detrimental to human health and high glucosinolate concentration in meal has a negative side effect on meal taste. The term canola is usually applied to *B. napus* cultivars especially developed for edible oil seed production. However, cultivars of other *Brassica* species such as *B. rapa*, *B. carinata*, and *B. juncea* have been selectivily breed to have low erucic acid oil and low glucosinate concentration in meal; therefore, these cultivars can be designated as canola. Within the canola industry, research is being conducted in an effort to increase yields per unit of area; however, unlike other crops such as soybeans (*Glycine max* (L.)

Merril) and corn (*Zea mays* L.) limited research has been performed on certain aspects of canola production. This is primarily due to canola acreage being dwarfed by soybean and corn hectarage within the United States of America.

One important aspect of canola oilseed production is the ability of canola to compensate for damage to the apical meristematic tissue caused by hail during various growth stages. In the past, hail studies on canola have been primarily focused on defoliation rather than stem damage (Kirkegaard et al., 2012; Ramachandran et al., 2000; Susko and Superfisky, 2009). The reason being that canola is a broadleaf crop and produces large broadleaves which have a large amount of susceptible surface area making it more vulnerable to hail damage resulting in defoliation. However, Fehr et al. (1983) reported that in a hail study conducted on soybeans, stem cut-off resulted in a greater seed yield loss compared to either defoliation or break over (stem is broken but still attached to the plant). The value of this research is the canola industry, crop insurance agencies, and producers will have a more accurate idea of the impact that stem cut-off damage has on canola seed yield (kg/hectare).

In the past, stand establishment studies on canola have primarily focused on addressing improper agronomic practices or seedling emergence issues due to abiotic stress (Angadi et al., 2003; Koenig et al., 2011; McCormick et al., 2013). These studies were primarily conducted in order to evaluate the ability of canola to compensate for an improper stand establishment. In most of these past studies treatments were performed on canola during vegetative growth stage by either hand pulling or hoeing out plants in order to replicate stand reduction treatments. However, a study conducted by McGregor (1987) showed that a stand density of 40 plants m^2 in the vegetative stage of growth could result a yield reduction of more than 20%. Additionally according to the canola production guide (Kandel and Knodel, 2011), a proper canola seeding

rate would be 1,500,000 PLS per hectare (roughly 151 PLS m^2) which usually provided an adequate established stand density of 86-130 plants m^{-2}.

The main objectives of this study were-

1. To study the response of seed yield of a glyphosate-resistant commercial canola hybrid to non-uniform stand reduction.

2. To study the response of seed yield of a glyphosate-resistant canola hybrid to stem cut-off.

3. To study yield component compensation of a glyphosate-resistant canola hybrid to both stand reduction and stem cut-off.

1.1. References

Angadi, S.V., H.W. Cutforth, B. G. McConkey, and Y. Gan. 2003. Yield adjustment by canola grown at different plant populations under semiarid conditions. Crop Sci. 43:1358-1366.

Fehr, W.R., D.R. Hicks, S.E. Hawkins, J.H. Ford, and W.W. Nelson. 1983. Soybean recovery from plant cutoff, breakover, and defoliation. Agron. J. 75:512-515.

Kandel, H., and J.J. Knodel. 2011. Canola production field guide. Bull. A-1280. NDSU Ext. Serv., Fargo, ND, USA.

Kirkegaard, J. A., S.J. Sprague, J. M. Lilley, J. I. McCormick, J. M. Virgona, and M. J. Morrison. 2012. Physiological response of spring canola (*Brassica napus*) to defoliation in diverse environments. Field Crops Research 125: 61-68.

McCormick, J.I., J.M.Virgona, and J.A. Kirkegaard. 2013. Regrowth of spring canola (*Brassica napus*) after defoliation. Plant and Soil 372: 655-668.

McGregor, D.I. 1987. Effect of plant density on development and yield of rapeseed and its significance to recovery from hail injury. Can. J. Pl. Sci. 67:43-45.

National Agricultural Services, USDA 2016. Crop production 2016 summary. [Online].

    Available at

    http://usda.mannlib.cornell.edu/usda/nass/CropProdSu//2010s/2017/CropProdSu-01-12-

    2017.pdf (verified 1 Nov. 2018).

Ramachandran, Suresh, G.D. Buntin, and J.N. All. 2000. Response of canola to simulated

    diamondback moth (*Lepidoptera: Plutellidae*) defoliation at different growth stages. Can.

    J. Pl. Sci. 80: 639-646.

Susko, D.J., and B.Superfisky. 2009. A comparison of artificial defoliation techniques using

    canola (*Brassica napus*). Plant Ecology 202: 169-175.

2. LITERATURE REVIEW

2.1. Rapeseed/ *Brassica napus* L.

2.1.1. History of rapeseed

The history of *Brassica napus* L. or rapeseed began with the initial creation and domestication of the species. *B. napus* is believed to have arisen around 7,500 years ago (Chalhoub et al., 2014) with some researchers having theorized that the origin of domestication took place in the Mediterranean region of southwestern Europe (Cruz et al., 2007; Rakow, 2004). There is evidence for the cultivation of the species in India as far back as 2000 BC (Colton and Podder, 1999).

Following initial domestication, human populations began selecting *B. napus* for a variety of purposes. Some of the uses for this species included its use as a leafy vegetable (Siberian kale), root crop (rutabagas), and as an oilseed crop (Soengas et al., 2008). Yet for most of its history, this species remained primarily a food crop for human populations.

It would not be until the middle ages that *B. napus* would be used as a commercial oil seed crop. However, the use of the oil would be limited to the purpose of producing oil to fuel lamps (Raymer, 2002). Large scale commercial production as an oil seed would occur during World War II in order to provide an industrial lubricant for naval ships.

It was around this time that a theory for the origin of *B. napus* was provided by Nagaharu (1935). This theory proposes the idea that *B. napus* arose from a spontaneous hybridization event between the diploid species, *B. rapa* (AA, 2n=20) and *B. oleracea* (CC, 2n=18) resulting in the allotetraploid hybrid, *B. napus* (AACC, 2n=4x=38) (Naraharu, 1935). This theory would eventually be known as the *Brassica* triangle of U.

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2.1.2. *Brassica* **triangle of U**

The *Brassica* triangle of U allows researchers to understand the genetic relationship between the different *Brassica* species in order to aid in genetic research. First purposed by Nagaharu (1935), the triangle of U purposes that the three diploid species *B. rapa* (AA, 2n=20), *B. nigra* (BB, 2n=16), and *B. oleracea* (CC, 2n=18) underwent interspecific hybridization resulting in amphidiploids such as *B. carinata* (BBCC, 2n=34), *B. juncea* (AABB, 2n=36), and *B. napus* (AACC, 2n=38). In the case of *B. napus*, it was believed to have arisen due to the spontaneous interspecific hybridization of the two diploid parent species, *B. rapa* (AA, 2n=20) and *B. oleracea* (CC, 2n=18) as illustrated in Fig. 2.1. The reasoning being that *B. napus* contains both the A and C genome which originate from both *B. rapa* and *B. oleracea*, respectively. This theory was later supported by a study conducted by Olsson (1960) in which viable *B. napus* was artificially synthesized by crossing diploid *B. oleracea* and tetraploid *B. rapa* (formally, *B. campestris*).
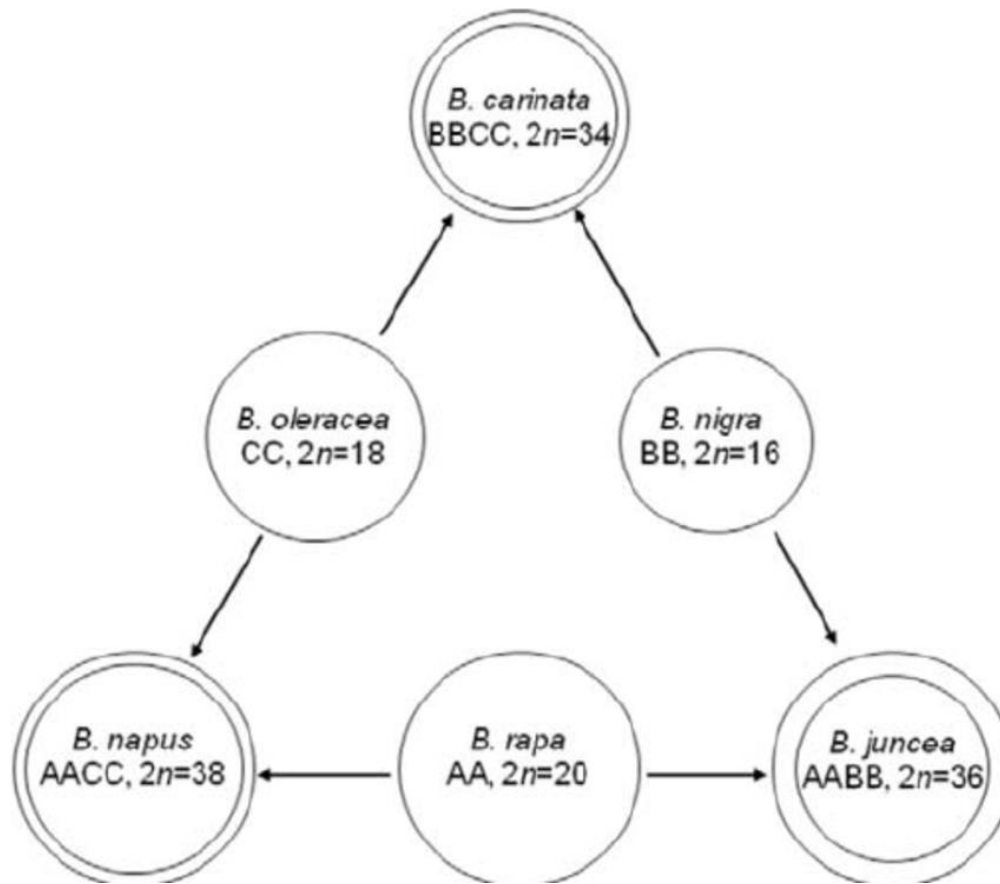
Figure 2.1. The genetic relationship amongst the six different Brassica species [sourced: Relationship of six natural Brassica species in the triangle of U (adapted from U 1935) "https://www.researchgate.net/figure/Relationship-of-six-natural-Brassica-species-in-the-triangle-of-U-adapted-from-U-1935_fig1_215662120"]

2.1.3. Taxonomy of rapeseed (*Brassica napus* L.)

The species *B. napus* belongs to the genus *Brassica* or the *Brassicaceae* family, commonly referred to as the mustard family. The *Brassicaceae* family consists of approximately 338 genera and 3709 species (Cheng et al., 2014). The *Brassica* genus itself contains 100 species including *B. napus*, commonly called oilseed rapeseed (Thomas, 2003). *B. napus* is a self-pollinating crop with an ability to undergo 12-47% crosspollination under optimal conditions (Becker et al., 1992). The flower of this species is bisexual and composed of four petals, four sepals, a pistil with two carpels and six stamens, the outer stamens are shorter than the rest. The flowers are arranged in a branching structure called a raceme. Pods are long and slender called

siliques which are a characteristic of the *Brassica* genus (Baily, 1976). Yet within the same species, *B. napus* has been selectively bred for different purposes and can be categorized into different groups.

2.2. Canola

2.2.1. Difference between canola and rapeseed

Two different sub groups for the *B. napus* species include canola and rapeseed. The canola is a term used to defined *Brassica* oilseed cultivars with low erucic acid content (<2%) and low glucosinolate content (less than 30 micromoles/gram) in the meal (Raymer, 2002). Rapeseed oilseed cultivars have such high levels of erucic acid and glucosinolate concentrations in the seed meal that they could not be used for human consumption. Canola is derived from "*Can*adian *O*il *L*ow *A*cid" and is a registered trade mark of the Canadian Canola Association. *B. napus* is the most common *Brassica* species given the designation of canola; however, other Brassica species such as *B. rapa, B. carinata,* and *B. juncea* have undergone extensive breeding work to be developed into cultivars that fit the definition of canola. Yet, the history of canola is intimately tied to the initial interest in rapeseed for an industrial application.

2.2.2. History of canola

The history of canola begins with the initial interest in rapeseed as an industrial lubricant for naval vessels during World War II which encouraged research and production of rapeseed in Canada. In 1954, the first registered rapeseed cultivar "Golden" was released which contained such high levels of erucic acid and glucosinolate concentration that it was rarely used outside of industrial applications (Stefansson, 1983). The *B. rapa* rapeseed cultivar "Liho" was released from the University of Manitoba which contained low levels erucic acid in (Stefansson and Hougen, 1963). However, "Liho" still had such high levels of glucosinolate that it was not

suitable for human consumption, so the search began for rapeseed lines which had low glucosinolate concentration. In 1967, a *B. napus* line called 'Bronowiski' was identified in Poland as having low glucosinolate concentration in the seed meal (Josefsson and Appelqvist, 1968). This discovery then led to Dr. Keith Downey transferring the low erucic acid characteristics from 'Liho` to a *B. napus* variety, 'Oro`, in 1968 (Downey, 2006). These two innovations then allowed for the development of 'double low' (low in erucic acid and glucosinolate) rapeseed lines. After several years of research primarily being conducted in Canada. The first annual rapeseed (*B. napus*) cultivar to meet the "canola" requirements was the cultivar 'Tower' developed by Dr. Baldur Stefansson at the University of Manitoba in 1974 (Stefansson and Kondra, 1975). Today, canola is the second most important vegetable oil producing crops after soybean (USDA, 2019). As a result, the production of canola has become an important industry in areas where this crop is grown.

2.2.3. Canola production

Canola production in the United States is relatively new with the production of canola oilseed beginning in the 1980s. However as of the 2017 growing season, North Dakota farmers planted 643,450 hectares of canola producing around 1.2 billion kg of canola oil seed valued at around $445 million (North Dakota Annual Bulletin, 2018). According to the Northern Canola Growers Association, canola acreage in 2018 remained around 647,497 hectares planted making North Dakota the largest producer of canola in the country with other states following suit. For instance, both Idaho and Minnesota farmers planted an additional 8,094 hectares in the 2018 season consisting mostly of spring type canola (NASS Annual Production Report, 2019). However, canola acreage dropped by 1,214 and 14,164 hectares in Kansas (winter canola) and Montana (spring canola), respectively (NASS Annual Production Report, 2019).

Canola production within North Dakota has historically been focused along the US-Canadian border stretching from Cavalier County to Burke County (Fig 2.2). The reason being that the climate in this area of the state tends to be characterized with a short growing season and cool climate which makes it more difficult to grow other crops such as corn and soybeans.

In recent years, the introduction of more drought/heat tolerant canola cultivars, combined with more soil moisture conservative practices such as no-till planting, has resulted in expanding canola acreage into more hail prone areas. Especially, the southwestern part of North Dakota which is known for being prone to large hail storms (Bonne, 1974). Additional reasons for expansion into the southwestern part of the states include the relative stability of canola prices, development of shatter proof cultivars, and lack of competition for acreage from other crops such as soybean (*Glycine max* (L.) Merril) and corn (*Zea mays* L.)

However, certain aspects of canola production still need to be addressed and researched. One of these aspects is the effect of hail damage on canola, as well as, the ability of canola to compensate for a stand reduction event.
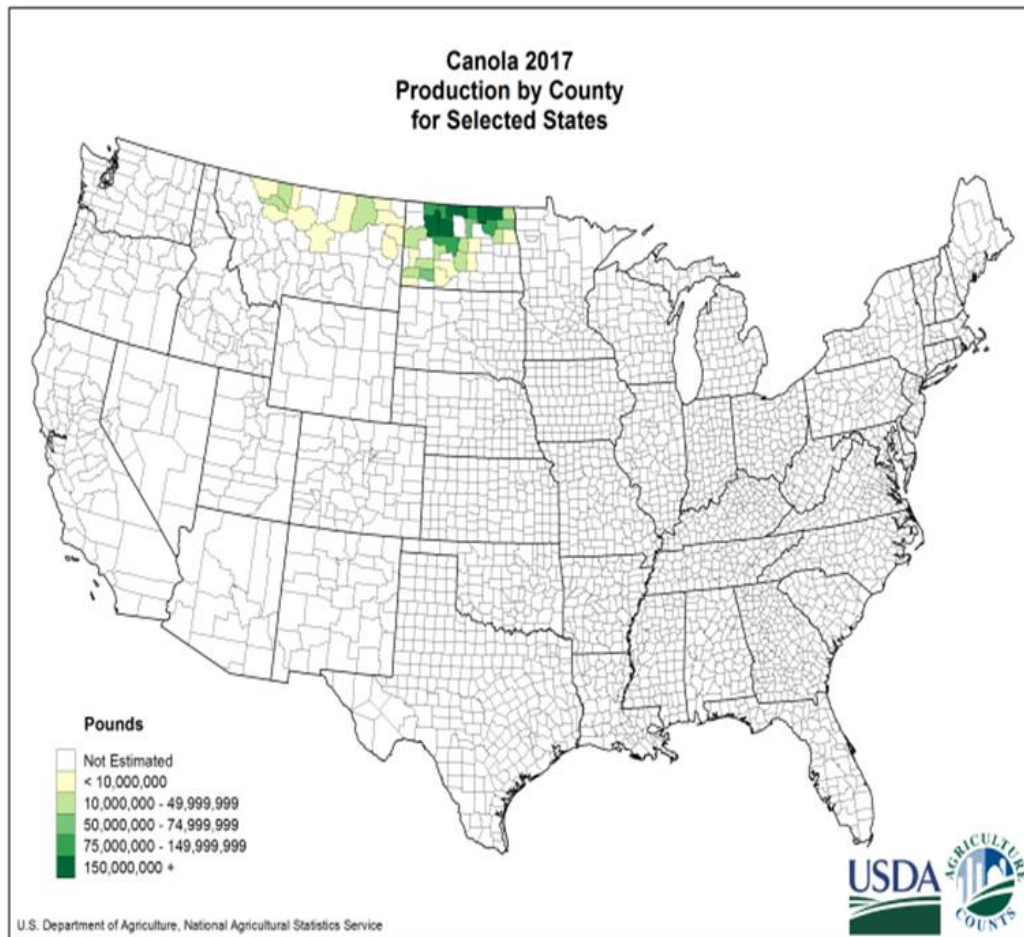
Figure 2.2. Production of canola in the United States [sourced: Canola: Production Acreage by County "https://www.nass.usda.gov/Charts_and_Maps/Crops_County/ca-pr.php"]

2.3. Hail studies on canola

According to Bonne (1974), North Dakota ranked in the top ten leading states for crop damage caused by hail with most of the damage occurring in the southwestern part of the state. Between the years 1960-1969, North Dakota ranked high in total economic losses caused by hail averaging an annual total of $5.5 million in losses from crop damage (Changnon, 1972).

In larger acreage crops such as soybean and corn, there has been an effort to evaluate the effects of different types of hail damage on seed yields. For reference during the 2017 season,

North Dakota planted 2.8 million hectares of soybeans and 1.3 million hectares of corn compared to just 643,450 million acres of canola (NASS, USDA, 2018).

Smaller hectarage crops such as canola have been largely understudied in respect to different types of hail damage effects on seed yield. Past studies on canola hail damage have been largely focused on characterizing the types of damage caused by hail and the effects of stand reduction resulting in plant death due to severe hail damage (McGregor, 1980; 1987). These studies observed that hail damage on canola was characterized largely by defoliation prior to bolting. However, after bolting, broken or bruised stems could be observed in the upper part of the canola plant as illustrated in Fig. 2.3. As far as the effect of stand reduction, canola had a large capacity to compensate for stand reduction occurring at the early vegetative growth stages.

In order to understand the effects of hail damage on canola, it is important to understand how hail studies have been conducted in the past on different crops. Crops with similar physiological and morphological traits will typically have a similar reaction to certain types of damage.

Figure 2.3. Canola after a severe hail storm [sourced: If you're going to feed hail-damaged crop to livestock, test it first "https://www.albertafarmexpress.ca/2016/08/09/if-youre-going-to-feed-hail-damaged-crop-to-livestock-test-it-first/ "]

2.4. Hail studies on different crops

2.4.1. Hail studies on dicotyledonous crops (defoliation)

Past hail studies on crops have been primarily focused on various types of damage caused by hail. These different types of damage include but are not limited to defoliation, stem cut-off, and stand reduction. This particular study is primarily concerned with the effects of stem severing on canola performance. However, in order to better understand hail damage, it is important to obtain a background knowledge on defoliation on different crops.

Crops like soybeans have a couple of physiological similarities with canola such as active hypocotyl emergence, similar growth habits, and belonging to the dicotyledonous (dicot) class of

crops. Dicotyledonous crops are defined as angiosperm plants that produce an embryo with two cotyledons (Merriam-Webster).

In a study conducted by Fehr et al. (1981), an indeterminate and determinate variety of soybean underwent defoliation treatments during the reproductive stages of growth, and the results showed that yield reduction was greatest in the determinate variety. Another observation made in this study was that both of the cultivars were affected the most by defoliation at the R5 growth stage or pod filling. These results are concurrent with studies conducted by Caviness and Thomas (1980), and Teigen and Vorst (1975).

Irigoyen et al. (2011) reported a similar trend in a defoliation study on potato (*Solanum tuberosum* L.) in which yield decreased significantly during tuber formation. The study revealed that in the growth stages before and after tuber formation, yield losses from defoliation were significantly lower than those of defoliation treatments during tuber formation. In potato, after tuber development is nearly complete, little yield loss would be expected, because the plant has already stored carbohydrates, created via photosynthesis in the green vegetative plant parts, in the tuber as starch. As a result, defoliation on the above ground tissue would have no effect on the tubers due to the plant allocating energy from photosynthesis towards starch production; therefore, the plant would not allocate energy stores away from the tuber to repair above ground tissue. These finds were supported by other hail studies conducted on potato by Jalali (2013) and Beresford (1967).

In another *Solanaceae* crop, Kretchman et al. (1989) demonstrated that in a defoliation study conducted on tomatoes that plants treated before fruit setting had less severe yield reduction compared to those plants treated during flowering and fruit development. The results showed a higher likelihood of a split-set (undamaged fruit on the plant continues to develop as

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the plant creates new fruit) occurring which would result in a yield decrease due to the undamaged fruit on the tomatoes plant rotting before mechanical harvesting can take place. However defoliation occurring before fruit-set only resulted in a delayed maturity of up to two weeks.

Similar trends have also been observed in onions, marketable yield decreased as defoliation intensity and growth stage increased (Bartolo et al., 1994). In onions, the growth stage which experienced the greatest yield reduction was at bulbing (onion plant is starting to accumulate storage compounds in the bulb of the onion plant). During this stage of development, the onion was more liable to experience infection from bacterial and fungal pathogen due to the foliar damage. Also, the leaves of the onion plant contain the receptor which stimulates bulbing activity; therefore, damage to leaves would likely interrupt the normal metabolic activities that result in bulbing.

Schneiter et al. (1987) performed a simulated hail damage study on hybrid sunflower in order to investigate the effects of defoliation at specific phenological stages of plant development. In this study, it was observed that defoliation was most detrimental to sunflower seed development and yield during the early reproductive stage (bud development). One hundred percent defoliation conducted at the last two growth stages (R3 and R4) resulted in the majority of the plants dying. Another observation made in this study was that, compared to before anthesis defoliation treatments conducted after anthesis had less effect on plant development as the seed filling process was partially complete. A previous study conducted by Sackston (1959) was the first to observe this trend in sunflower stating that high levels of defoliation conducted at the flowering stage resulted in a sharp yield decrease. Later on, Muro et al. (2001) supported this

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trend in stating that sunflower experienced the greatest yield decrease when defoliation took place during the pre-flowering growth stage (R3).

In a hail study conducted on guar (*Cyamopsis tetragonoloba* L. Taub.), it was observed that plants could recover from hail damage when defoliation was conducted at early growth stages, as long as, the environment was conducive for plant growth. Guar has a largely indeterminate growth habit. As a result, the plants have the ability to regrow and recover yield potential, as long as, the season is long enough and water is available to aid in recovery (Sij et al., 2005). It is likely that canola could have this same ability in regards to defoliation if the environment is near optimal. Like guar, canola has an indeterminate growth (Koenig et al., 2011) habit meaning that the plants could remain in the vegetative stage for a longer time in order to better recover from defoliation.

After evaluating these studies it could be reasoned that canola would experience a significant yield decrease as the plants switch from the vegetative stage of growth to the reproductive growth stage. One must keep in mind that canola has largely an indeterminate growth habit meaning that the plant can keep flowering even as the fruits are starting to be formed on the plants. This could affect plant performance because defoliation during the bolting stage might result in delayed maturity which would be less detrimental given that there are adequate conditions and days until harvest in order to recover. Yet, defoliation is not the only type of damage observed during a hail storm.

2.4.2. Hail studies on dicotyledonous crops (stem cut-off)

Hail damage on dicot crops results in primarily two types of damage, broken stems and defoliation. Defoliation which was discussed in the previous section is usually most detrimental during the transition from vegetative to reproductive growth phase. In addition, both types of

damage can result in a higher likelihood of infection from fungal or bacterial pathogens. However with respect to yield, stem damage is a more critical factor in certain crops.

Fehr et al. (1983) observed that stem cut-off of the upper half of a plants height in soybean (*Glycine max*) resulted in greater seed yield reduction than either leaf defoliation or break-over (stem is broken but still attached to the plant) in both the vegetative and reproductive growth stages. As a result of the upper half of the plant being removed, the seed yields were reduced due to the loss of apical and axial meristematic regions. These regions are important contributors to final yield since meristematic regions have the ability to differentiate into branches or pods which are crucial yield determining factors. The loss of these regions is detrimental to yield, because the plants possess fewer meristematic regions which are critical for developing yield components which contribute to the overall yield of a field. A similar trend in lentils (*Lens culinaris*) was reported in which plants underwent simulated hail damage caused by a flail (causes both defoliation and stem damage) had 28% yield reduction at vegetative stages, 37% yield reduction at early flowering stage, and 45% yield reduction at pod-fill and physiological maturity stage (Bueckert, 2011). Hail damage in the later growths stages was found to be more devastating to seed yields.

As the physiological maturity of the plant increases, the ability of the plant to compensate for vegetative damage decreases due to the absence of ways to compensate. Miller and Muehlbaur (1984) observed that in sweet pea (*Pisum sativum* L.), yields declined by 0.59% for each 1% increase in the number of damaged plants in the reproductive stage when the plants were cut between the first and second flowering node, and a 0.85% decline in yield when cut below the first flowering node. During reproductive stages of plant development, energy investment within the plant is being dedicated to the development of reproductive organs and

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seed development. As a result, stem damage being administered during the reproductive growth stage is detrimental to overall seed production, because damage of photosynthetic tissue will result in less photosynthate production.

Soine (1970) reported that stem breaking in flax (*Linum usitatissimum* L.) resulted in the greatest injury and yield reduction compared to the check plots, especially when the plants reached the mature boll stage. The recurring trend in dicots and monocots is that as the plants reach maturity, the ability for the plants to compensate for vegetative stem damage decreases. The loss of the meristematic regions due to cut-off results in greater yield reduction, because the few secondary meristematic regions (axial buds) that remain cannot compensate for the damage due to fewer growing points and lack of maturity. Stem cut-off damage that is the result of hail damage on dicotyledonous crops has a higher yield reduction than defoliation when the crops reaches the reproductive growth stages. Yet, dicot crops are not the only classes of crops to experience hail. In fact, monocotyledonous (monocot) crops have underwent extensive studies on the effect of hail damage on crop performance.

2.4.3. Hail studies on monocotyledonous crops (defoliation)

Monocotyledonous (monocot) crops are defined as angiosperm plants that have an embryo with a single cotyledon (Merriam-Webster). These crops are critical from a global perspective. The reason being that this group provides most of the world carbohydrates. Some important crops that belong to this category consist of maize, wheat, sorghum, rice, barley, and millet.

In a hail study conducted by Lauer et al. (2004) on corn forage, it was observed that defoliation treatments had little effect on yield when defoliation occurred during the early vegetative growth stages. However, the 100% defoliation treatments decreased forage yields by

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43% at V10, 70% at R1, and 40% at R4 growth stages. According to Lauer (2009), most of the yield reduction from a hail event is caused by defoliation in corn. Corn has large leaves and plants are planted relatively dense to achieve a stand of 81,510 – 86,450 plants hectare[-1] (Van Roekel and Coulter, 2011). Due to the large biomass and the stem being protected by leaf sheets, defoliation is more likely to occur than stem bruising in corn. However, a potential risk of stem bruising is the chance of infection from fungal and bacterial pathogens.

A similar trend can be observed when looking at defoliation in sorghum (*Sorghum bicolor*). According to Strickler and Pauli (1961), defoliation below 50% in sorghum resulted in very little seed yield reduction when treated during booting and anthesis. An extension article from the University of Nebraska-Lincoln supports this trend in which defoliation over 50% was most detrimental to sorghum grain production when defoliation took place from the 15-leaf stage to the milking stage (Shapiro and Peterson, 1997). In sorghum, defoliation treatments have also been shown to slow grain filling, and increase lodging and stalk rot (Rajewski and Francis, 1991). However, these side effects are largely influenced by environmental variation.

In a study conducted by Counce et al. (1994) in rice (*Oryza sativa*), defoliation had the greatest impact on yield reduction when the rice plants where defoliated down to 10 cm about the soil surface at panicle initiation. Interesting, seed yield did increase when plants were defoliated to 3 cm at pretillering and lodging decreased from 60% (control) to 15%. The article states that this could be the result of delaying tillering and the fact that there is less leaf area for pretillering defoliation.

With the exception of these major cereal crops, monocot crop have had little hail studies conducted on them specifically pertaining to the subject of defoliation. Most monocot crops have less surface area compared to dicots. Additionally, planting densities for monocots such as cereal

grains tend to be higher compared to dicots which makes defoliation studies on a per plant basis more challenging. As a result, hail studies conducted on monocots tend to be more concerned with the effect of apical meristem damage to the plant, since this region of the plant is responsible for grain development (one exception being corn). However, more research should be conducted in order to determine the effects of defoliation on monocot crops.

2.4.4. Hail studies on monocotyledonous crops (stem cut-off)

Unlike defoliation, there has been a significant amount of research conducted to assess the effects of stem damage on monocot crops. In general, monocot crops have shown a higher capacity to withstand hail damage resulting in stem damage or defoliation compared to dicot crops.

For example, stem cut-off is not as important in terms of yield reduction, however plants that are further along in development due experience significant yield reduction even though every plant has multiple tillers expect in the case of corn.

Dwyer et al. (1994) observed a seed yield reduction of 30 – 35% in a corn field that had experienced a hail storm. Plants that had broken stalks below the ear would not recover resulting in less plants being able to contribute to the overall yield. They also showed that the severity of damage increased as the crop reached maturity stage R5-6 (Dwyer et al., 1994). Less mature monocots compensate for hail damage by investing more energy into tillers allowing them to compensate for the lost growing points more efficiently. Unlike dicots that don't branch, a monocot has multiple apical growing points emerging from every plant in the form of tillers. Tillers compensate for the lost main head by producing additional heads with more seeds.

Gilbertson and Hockett (1979) reported a similar trend in barley (*Hordeum vulgare* L.) which revealed that yield reductions became more severe as the plants approached heading

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(Zadox stage 60). As plants approach the reproductive stages of growth, the effect of vegetable damage is critical due to the leaf area of the plant being decreased resulting in less photosynthate going to seed production resulting in lower yields. Additionally, damaged plants will experience delayed maturity due to the decreased leaf area resulting in less energy going toward seed production resulting in delayed maturity.

However, Shanaha et al. (2000) observed in proso millet (*Panicum miliaceum*) that yield reduction as a result of shoot reduction was greatest at emergence and recommended that farmers should consider replanting if shoot reduction exceeded 66%. Shoot reduction enacted at the booting growth stage still did diminish yield significantly, but not to the same effect as at emergence. Unlike other monocots, proso millet does not possess the ability to tiller until weeks after emergence. As a result, shoot reduction during emergence results in plant death and stand reduction; however, plants that are still emerging may still be able to compensate for stand reduction.

As plants continue in development, both monocots and dicots experience a lessening ability to compensate for vegetative damage resulting in greater seed yield reductions. In dicots, the type of damage plays a significant role in the total yield reduction expected from damage to the main stem. The reason being that monocots can compensate to a greater extent by investing more energy into the already forming tillers. In order to understand the impact of stem breakage on canola, a simulated hail study needs to be performed in order to determine the yield response of canola to this type of damage. However, hail damage is not only limited to stem damage, but more so, stand reduction is another type of damage observed after a heavy hail event.

2.5. Stand reduction studies on canola

Stand reduction is a critical component of crop production to understand. The reason being that the most important yield component in any cropping system is stand establishment (Dr. Burton Johnson, personal communication). Achieving a full and uniform stand is important for crop performance and seed yields in any crop. Non-uniform stand results in exposed soil to the sun and optimal conditions for weeds to compete with the crop for resources resulting in a yield decrease. Also, planting seeds at too high of a rate results in increase interplant competition, and low seeding rates result in more exposed soil to sunlight were weeds can grow and compete with the plants. In the case of canola, an ideal seeding rate of 1,500,000 pure live seeds (PLS) per hectare (roughly 151 PLS m^{-2}) usually provided an adequate established stand density of 86-130 plants m^{-2} (Kandel and Knodel, 2011).

Stand reduction can be the result of several environmental conditions such as frost, flooding, soil crusting, and/or hail. Since, a severe hail storm event can result in stand reduction; it is a crucial aspect to study in order to understand how plants performance is impacted. However with regards to canola, little is known about how canola responds to non-uniform stand reduction at different growth stages throughout development.

One of the main objectives of this study is to evaluate how canola compensates for this particular type of stand reduction. Originally the method of compensation reported by Major (1977) showed that the yield component seeds per pod increased as stand density decreased in canola. Later both McGregor (1987) and Angadi et al. (2003) reported the yield component of pods per plant was more important than seeds per pod in yield compensation when stand reduction occurred. However, these studies were performed on canola during the seedling or

early vegetative stages of growth. Knowing that canola belongs to the dicotyledonous class of crops; it is important to understand how stand reduction effects these crops.

2.5.1. Stand reduction studies on dicotyledonous crops

Dicots are particularly prone to stand reduction resulting from hail damage. Most important dicot crops have an active hypocotyl emergence which means that the first node is above the soil surface. If the plant stem is severed below the first node, the plant cannot recover, resulting in stand reduction. However, hail damage is not uniform with regards to stand reduction. It is crucial to understand how the surviving plants compensate for the reduced stand. As a result, an objective of this study was to determine how the remaining plants compensate for a reduced stand.

The United States is the second largest exporter of soybeans in global trade, comprising approximately 38% of all soybean exports (OEC, 2019). As a result of the economic importance of soybeans, there has considerable investment toward understanding the effect of stand reduction on soybean performance. Teigen and Vorst (1975) reported that the remaining plants compensated for stand reduction by producing more pods per plant and seeds per pod as stand reductions increased, resulting in yield compensation to a degree. This same observation was made by Caviness and Miner (1962), Burmood and Fehr (1973), and Camery and Weber (1953). These studies also observed that stand reduction was most detrimental to seed yield when stand reduction was enacted at the flowering stage of development.

Casa et al. (1999) described a similar relationship in flax where compensation for lower plant densities was achieved by producing more bolls per plant. In dicots such as soybean and flax, stand reduction compensation is achieved primarily by producing more pods or bolls per plants rather than seeds per pod or boll. The remaining plants utilized nutrients and water in the

soil which would otherwise not have been available due to competition between plants at higher planting densities.

Miller and Roath (1982) observed that sunflower (*Helianthus annuus* L.) compensated for stand reduction by increasing seed weight and head diameter. The seed head of sunflower is a composite flower head meaning that it is composed of multiple individual flowers each capable of producing a seed. The surviving plants utilize the extra available nutrients in the soil to produce more flowers per head resulting in a greater seed yield than under normal field conditions.

A recurring theme observed in stand reduction in monocots is that compensation for a reduced stand is related to the increased number of tillers and greater allocation of energy to the seed heads ultimately resulting in higher yields on a plant by plant basis. A similar means of compensation can be observed in dicots in which the methods of compensation is primarily related to increased pod production and a greater number of seeds per pod. Additionally, it is important to understand how crops in the monocotyledonous class respond to a stand reduction event.

2.5.2. Stand reduction studies on monocotyledonous crops

In monocots, the method of compensation is to form more tillers and investment of more photosynthates into producing more seeds per head (or ears in the case of corn). Larson and Vanderlip (1994) described that sorghum (*Sorghum bicolor* L.) compensated for stand reduction enacted at 12-15 days after emergence by producing more tillers per plant, panicles per plant, seeds per head, and greater seed weight under both uniform and non-uniform conditions which showed no significant difference in yield between the two types of stand reduction. According to the authors, sorghum compensates for stand reduction by investing more energy into tillers in the

remaining plants. Sorghum is a member of the monocot class of crops meaning like other monocots with the exception of corn. It can compensate for damage to the main stem or lower stands by investing more energy into the tillers and the seed heads.

Coulter et al. (2011) reported that in corn, grain yields increased by 37 to 46% per plant when undergoing 50% stand reduction at the V11 or V15 growth stage. However, unlike other monocots, field corn does not have the ability to form productive tillers. As a result, remaining plants compensated for stand reduction by producing more kernels per plant. This was accomplished by producing more kernels per ear on each of the surviving plants.

Holen et al. (2001) showed that in winter wheat (*Triticum aestivum* L.), a stand establishment that was 40-50% of the optimal stand (140 plants m^{-2}) would have a seed yield equal to those of spring wheat varieties with an optimal stand in the same environments. The reason being that winter wheat is planted in the fall and germinates early in the spring. As a result, the seedling have more time in the spring to accumulate photosynthates and produce more tillers and kernels per head in order to compensate for stand reduction. The recurring trend in monocots is that these type of plants compensate for stand reduction by producing more seed yield per plant by producing more tillers resulting in a greater seed yield per plant.

2.6. References

Angadi, S.V., H.W. Cutforth, B. G. McConkey, and Y. Gan. 2003. Yield adjustment by canola grown at different plant populations under semiarid conditions. Crop Sci. 43:1358-1366.

Baily, L.H. 1976. Hortus Third- A concise dictionary of plants cultivated in the United States and Canada. McMillan General reference, New York. 1290.

Bartolo, M. E., H.F. Schwartz, and F.C. Schweissing. 1994. Yield and growth response of onion to simulated storm damage. Hort. Sci. 29: 1465-1467.

Becker, H. C., R. Karle and S.S. Han. 1992. Environmental variation for outcrossing rates in rapeseed (*B. napus*). Theor. Appl. Genet. 84:303-306.

Beresford, B.C. 1967. Effect of simulated hail damage on yield and quality of potatoes. Amer. Potato J. 44: 347-354.

Boone, L. M. 1974. Estimating crop losses due to hail. Agricultural Economics Report 267, U.S.D.A., Washington, D.C.

Bueckert, R.A. 2011. Simulated hail damage and yield reduction in lentil. Can. J. Plant Sci. 91:117-124.

Burmood, D. T., and W. R. Fehr. 1973. Variety and row spacing effects on recoverability of soybeans from simulated hail injury 1. Agron. J. 65: 301-303.

Camery, M.P., and C.R. Weber. 1953. Effects of certain components of simulated hail injury on soybeans and corn. Research Bulletin (Iowa Agriculture and Home Economics Experiment Station). 31: 1.

Casa, R., G. Russell, B.L. Cascio, and F. Rossini. 1999. Environmental effects on linseed (*Linum usitatissimum* L.) yield and growth of flax at different stand densities. Eur. J. Agron. 11:267-278.

Caviness, C.E., and F.D. Miner. 1962. Effects of stand reduction in soybeans simulating three-cornered alfalfa hopper injury1. Agron. J. 54: 300-302.

Caviness, C.E., and J.D. Thomas. 1980. Yield reduction from defoliation of irrigated and non-irrigated soybeans 1. Agron. J. 72: 977-980.

Chalhoub, B., F. Denoeud, S. Liu, I.A. Parkin, H. Tang, X. Wang, J. Chiquet et al. 2014. Early allopolyploid evolution in the post-Neolithic *B. napus* oilseed genome. Science 345: 950-953.

Changnon Jr., S.A. 1972. Examples of economic losses, from hail in the United States. J. Appl. Meteorol. 11:1128-1137.

Cheng, F., Wu, J. and X. Wang. 2014. Genome triplication drove the diversification of *Brassica* plants. Hort. Res.1: 14024.

Colton, B. and T. Potter. 1999. History. In P.A. Salisbury, T. Potter, G. McDonald, AGGreen, (eds) Canola in Australia: The first thirty years. 10th International Rapeseed Congress. 1-4.

Coulter, J.A., E.D. Nafziger, L.J. Abendroth, P.R. Thomison, R.W. Elmore, and M.E. Zarnstorff. 2011. Agronomic responses of corn to stand reduction at vegetative growth stages. Agron. J. 103: 577-583.

Counce, P.A., B.R. Wells, and R.J. Norman. 1994. Simulated hail damage to rice: I. Susceptible growth stages. Agron. J. 86: 1107-1113.

Cruz, V.M.V., R. Luhman, L.F. Marek, C.L. Rife, R.C. Shoemaker, E.C. Brummer and C.A.C. Gardner. 2007. Characterization of flowering time and SSR marker analysis of spring and winter type *B. napus* L. germplasm. Euphytica 153: 43-57.

Downey, R.K. 2006 Rapeseed to canola: Rags to riches. NABC.

Dwyer, L. M., D. W. Stewart, L. Evenson, and B.L. Ma. 1994. Maize growth and yield following late summer hail. Crop Sci. 34: 1400-1403.

Fehr, W. R., D. R. Hicks, S. E. Hawkins, J. H. Ford, and W.W. Nelson. 1983. Soybean recovery from plant cutoff, breakover, and defoliation 1. Agron. J. 75: 512-515.

Fehr, W.R., B.K. Lawrence, and T.A. Thompson. 1981. Critical stages of development for defoliation of soybean 1. Crop Sci. 21: 259-262.

Gilbertson, K. M., and E. A. Hockett. 1979. The effect of hail damage on barley. Can. J. Plant
Sci. 59: 1147-1152.

Holen, D.L., Philip L. Bruckner, J.M. Martin, G.R. Carlson, D.M. Wichman, and J.E. Berg.
2001. Response of winter wheat to simulated stand reduction. Agron. J. 93: 364-370.

Irigoyen, I., I. Domeño, and J. Muro. 2011. Effect of defoliation by simulated hail damage on
yield of potato cultivars with different maturity performed in Spain. Amer. J. Potato
Research 88: 82-90.

Jalali, A.H. 2013. Potato (*Solanum tuberosum* L.) yield response to simulated hail damage.
Archives of Agron.and Soil Sci. 59: 981-987.

Josefsson, E., and L.Å. Appelqvist. 1968. Glucosinolates in seed of rape and turnip rape as
affected by variety and environment. J. Sci. of Food and Agri. 19: 564-570.

Kandel, H., and J.J. Knodel. 2011. Canola production field guide. Bull. A-1280. NDSU Ext.
Serv., Fargo, ND.

Koenig, R.T., W.A. Hammac, and W.L. Pan. 2011. Canola growth, development and fertility.
Washington State University Extension Fact Sheet FS045E, Pullman, WA.

Kretchman, D., Jameson, M. and Willer, C., 1989. Effects of simulated hail on processing
tomatoes. OSU Dept. Hort., Wooster, Ohio, USA.

Larson, E.J., and R.L. Vanderlip. 1994. Grain sorghum yield response to nonuniform stand
reductions. Agron. J. 86: 475-477.

Lauer, J. G., G. W. Roth, and M.G. Bertram. 2004. Impact of defoliation on corn forage yield.
Agron. J. 96: 1459-1463.

Lauer, J. 1977. 2009. Late-season hail effects on corn. Agro. Advice, Univ. of Wisc. (2009).

Major, J.D. 1977. Influence of seed size on yield and yield components of rape. Agron. J. 69:541-543.

McGregor, D.I. 1980. The nature of hail injury in Rapeseed. Can. J. Pl. Sci. 60:1441-1449.

McGregor, D.I. 1987. Effect of plant density on development and yield of rapeseed and its significance to recovery from hail injury. Can. J. Pl. Sci. 67:43-45.

Merriam-Webster. [Online] dictionary https://www.merriam-webster.com/

Miller, J. F., and W. W. Roath. 1982. Compensatory response of sunflower to stand reduction applied at different plant growth stages 1. Agron. J. 74: 119-121.

Miller, D. G., and F. J. Muehlbauer. 1984. Stem excision as a means of simulating hail injury on 'Alaska'Peas 1. Agron. J. 76: 1003-1005.

Muro, J., I. Irigoyen, A.F. Militino, and C. Lamsfus. 2001. Defoliation effects on sunflower yield reduction. Agron. J. 93: 634-637.

Nagaharu, U. 1935. Genome analysis in *Brassica* with special reference to the experimental formation of B. napus and peculiar mode of fertilization. Japan. J. Bot. 7: 389–452.

National Agricultural Statistics Services, USDA, 2017. National statistics on canola. [Online]. Available on https://www.nass.usda.gov/Statistics_by_Subject/result.php?0E68EF75-BFF0-3FD0-863B 9E905C6FE215&sector=CROPS&group=FIELD%20CROPS&comm=CANOLA (verified 1 Feb. 2018).

National Agricultural Statistics Service, USDA, 2018. 2018 State agricultural overview: North Dakota. [Online]. Available on https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NORTH %20DAKOTA (verified 1 Jan. 2019).

NASS Annual Production Report, 2019. Canola area planted and harvested, yield and

      production: 2016-2018. [Online]. Available on http://www.uscanola.com/crop-

      production/ (verified on 10 Dec. 2018).

North Dakota Annual Bulletin, 2018. Canola acreage, yield, production, price, and value North

      Dakota: 2008-2017. [Online]. Available on

      https://www.nass.usda.gov/Statistics_by_State/North_Dakota/Publications/Annual_Statis

      tical_Bulletin/2018/ND-Annual-Bulletin18.pdf (verified 1 Jan. 2019).

OEC. 2019. Soybeans product trade, exporters, and importers. [Online]. Available on

      https://atlas.media.mit.edu/en/profile/hs92/1201/ (verified 11 April 2019).

Olsson, G. 1960. Species crossing within the genus *Brassica* II. artificial *Brassica napus* L.

      Hereditas 46: 357-396.

Rajewski, J. F., and C. A. Francis. 1991. Defoliation effects on grain fill, stalk rot, and lodging of

      grain sorghum. Crop Sci. 31: 353-359.

Raymer, P.L. 2002. Canola: An emerging oilseed crop. ASHS Press, Alexandria, VA. 122–126.

Rakow, G. 2004. Species origin and economic importance of *Brassica*. Springer, Berlin

      Heidelberg.

Sackston, W.E., 1959. Effects of artificial defoliation on sunflowers. Can. J. of Plant Sci. 39:

      108-118.

Schneiter, A., J. M. Jones, and J. J. Hammond. 1987. Simulated hail research in sunflower:

      defoliation 1. Agron. J. 79: 431-434.

Shanahan, J., B. Schatz, D. Baltensperger, J. Sooby, and S. Kachman. 2000. Use of shoot

      reduction treatments as a means of simulating hail injury to proso millet. Comm. in Soil

      Sci. and Plant analy. 31: 2843-2854.

Shapiro, C.A., and T.A. Peterson. 1997. Sorghum yield loss due to hail damage. UNL Coop. Ext., Lincoln, NE.

Soengas, P., M.E. Cartea, P. Velasco, G. Padilla, and A. Ordás. 2008. Morphologic and agronomic diversity of *Brassica napus* crops. J. of the Amer. Society for Hort. Sci. 133: 48-54.

Soine, O.C. 1970. Effect of simulated hail damage on flax. Agricultural Experiment Station, University of Minnesota, Miscellaneous Report 92.

Stefansson, B.R., and Z.P. Kondra. 1975. Tower summer rape. Can. J. of Plant Sci. 55: 343-344.

Stefansson, B.R., 1983. Development of improved rapeseed cultivars. High and low erucic acid rapeseed oils: production, usage, chemistry, and toxicological evaluation/edited by JKG Kramer, FD Sauer, WJ Pigden.

Stefansson, B. R., and F.W. Hougen 1963. Selection of rape plants (*Brassica napus*) with seed oil practically free from erucic acid. Can. J. Plant Sci. 55: 359-364.

Stickler, F. C., and A.W. Pauli. 1961. Leaf removal in grain sorghum. I. effects of certain defoliation treatments on yield and components of yield 1. Agron. J. 53: 99-102.

Sij, J.W., J.P. Ott, B.L.Olson, and T.A. Baughman. 2005. Growth and yield response to simulated hail damage in guar. Agron. J. 97: 1636-1639.

Teigen, J.R., and J.J. Vorst. 1975. Soybean response to stand reduction and defoliation 1. Agron. J. 67: 813-816.

Thomas, P. 2003. Canola growers manual. The canola council of Canada. [Online]. Available from http://canolacouncil.org/crop-production/canola-grower's-manual-contents/chapter-2-canola-varieties/canola-varieties#brassica (verified 23 Sept. 2018).

United States Department of Agriculture, 2019. Oilseeds: world markets and trade. [Online]. Avaialble on https://apps.fas.usda.gov/psdonline/circulars/oilseeds.pdf (verified 7 April 2019).

Van Roekel, R.J. and J.A. Coulter. 2011. Agronomic responses of corn to planting date and plant density. Agron. J. 103: 1414-1422.

3. NON-UNIFORM STAND REDUCTION STUDY

3.1. Abstract

Natural hail can cause significant damage on seed yield and yield contributing traits of canola. Hail damage can be assessed by the type of damages such as stand reduction or stem cut-off, level of damage, plant growth stages etc. In this research, a simulated hail damage study was conducted based on various levels of plant reduction on four different growth stages. The experiment was conducted at five environments using a factorial arrangement with two factors, four growth stages and five levels of stand reduction, and randomized four times within them. Data on seed yield, seed oil, seed protein from each plot, and yield contributing traits from twenty plants per treatment were taken. Seed yield losses increased as both growth stages and levels of stand reduction increased. From the plot yield data, a regression equation was developed from this study to estimate the yield reduction across different levels of stand reduction at four growth stages. Seed yield plant^{-1}, pods plant^{-1}, and seeds pod^{-1} increased as the stand reduction increased, but decreased as the growth stages increased. The findings of differential yield losses by stand reduction will help producers and crop adjusters to quickly and accurately assess the severity of hail damage in canola.

3.2. Introduction

The word canola is derived from "Canadian Oil Low Acid" due to its low erucic acid content (<2%) and low glucosinolate content (less than 30 micromoles/gram) in the meal (Raymer, 2002). North Dakota is the largest domestic producer of canola with about 84% of all the hectares planted in the United States, 86% of harvested hectarage, and valued at around $403 million dollars (NASS, USDA, 2018). Traditionally, canola production in North Dakota has been largely limited to the counties along the United States and Canadian border due to favorable

moisture and climate. However, there has been an expansion of hectarage within the past two decades in different areas of North Dakota and other areas in the United States.

The increase in canola hectarage in North Dakota can be attributed to the relative stability and profitability of canola seed prices. Shatter resistant canola cultivars has also made canola production more attractive to producers due to ease of harvest, as well as, the decreased risk of volunteer canola in the preceding season. Additionally, more drought/heat tolerant canola cultivars combined with more conservative tillage practices such as no-till or minimum tillage has resulted in increased production in more drought prone areas such as southwestern North Dakota.

In fact, this region of the state has seen an increase in land devoted towards canola production. The climate of this part of the state is prone to drought and unpredictable weather patterns. One of the production challenges facing this portion of the state is the constant threat of hail damage (Boone, 1974). In fact between the years 1960-1969, North Dakota as a whole ranked high in total economic losses caused by hail, averaging an annual total of $5.5 million dollars in losses from crop damage (Changnon, 1972). However, canola has considerably less area dedicated to production compared to other major crops such as maize (*Zea mays* L.) or soybeans (*Glycine max* L. Merril) in the United States.

Hail studies conducted on canola are rarely done due to lack of interest and funding. Hail damage can be a major yield limiting factor which is dependent on various aspects such as type of damage, level of damage, and stage of development of the crop. One type of damage which can be the resulted by hail is stand reduction. McGregor (1980) demonstrated that a severe stand reduction event of less than 40 canola plants per m^2 (40% of an optimal stand) could expect a yield reduction of 20% or more when administered at the vegetative phase of growth. However,

it is critical to understand how canola would recover from varying degrees of stand reduction at various growth stages. Stand reduction can occur at any time in the season from not only hail but also high winds, heavy insect pressure, high disease pressure, and weed competition (Canola Council of Canada, 2017).

Understanding the response of seed yield to stand reduction is important, because it allows producers/insurers to evaluate the effect of stand reduction on seed yield and thus profit potential. Therefore, the objective of this study was to determine the effects of simulated hail damage by stand reduction on seed yield and yield contributing traits of canola.

3.3. Materials and methods

3.3.1. Experimental design

The experiment was conducted using a randomized complete block design with a factorial arrangement with two factors in both 2017 and 2018 growing seasons. One factor was the growth stages at which the plots received treatment. While the other factor was the levels of stand reduction with all combinations being observed within each replication. Both of these factors were considered fixed effects; whereas, environments (each location and year combination) was considered a random effect. The experiments were conducted with four replicates of each growth stage and levels of stand reduction combination at each of three locations. Ammonium sulfate and urea fertilizers were applied to attain a canola seed yield goal of at least 2,242 kg ha^{-1}at Carrington, 2,242 kg ha^{-1} at Prosper, and 2,802 kg ha^{-1} at Langdon. Trifluralin was used as a pre-emergence herbicide, and Glyphosate was used for post-emergence control of weeds. The plot size was 1.3 m x 4.6 m. The seeding rate was 6 kg ha^{-1} or 1,075,000 seeds ha^{-1}. Initial crop stand was determined by counting the number of plants m^{-2} with two measurements taken per plot at the 2.4 to 2.5 growth stage at each location. Final crop stand was

determined after harvesting by counting all of the stubble stems in every test plot divided by the area of the plot.

3.3.2. Plant materials

A spring type commercial hybrid canola cultivar 'DKL 70-10' acquired from Monsanto was used in this study. This cultivar is glyphosate and blackleg resistant and was released by Dekalb, a subsidiary of Monsanto Company, Creve Coeur, Missouri, US. 'DKL 70-10' was chosen due to the fact that it is a spring hybrid cultivar commonly grown in North Dakota.

All seeds received a seed treatment before being planted. The seed treatment was Helix Xtra (Syngenta, USA), a systemic insecticide belonging to the neonicotinoid family used primarily for the early season control of the crucifer flea beetle (*Phyllotreta cruciferae* (Goeze)) as well as a fungicide against seed-borne blackleg, *Alternaria,* and the seedling disease complexes.

The experiment was planted in three different locations in both 2017 and 2018. In 2017, the experiment was planted at Carrington on May 9, Prosper on May 12, and Langdon on May 19. These plots were harvested on August 29 at Carrington, Prosper on September 4, and Langdon on September 13 in the 2017. During the 2018 season, this experiment was planted at Carrington on May 14, Langdon on May 15, and Prosper on May 22, and plots were harvested on August 29 at Carrington and September 9 at Prosper. The 2018 Langdon trial was abandoned due to factors discussed later.

3.3.3. Stand reduction

In order to simulate hail damage, a stand reduction experiment was conducted at four different growth stages. The first growth stage was the 4th to 5th leaf rosette growth stage or growth stage 2.4 to 2.5 according to Harper and Berkenkamp (1975), refer in the Fig. 3.1. The

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second growth stage was bolting or stage 3.1 to 3.2, the third stage of treatment was 50%

flowering (when 15 to 20 flowers begin to open on the main stem) or stage 3.3 to 4.1, and the

fourth stage of treatment was administered at 90% flowering (flowering is beginning to slow

down and the lower pods have started to fill) or stage 4.3 to 4.4 (Fig. 3.1).

Fig. 1.   Key to the growth stages in rape (*Brassica campestris* and *B. napus*).
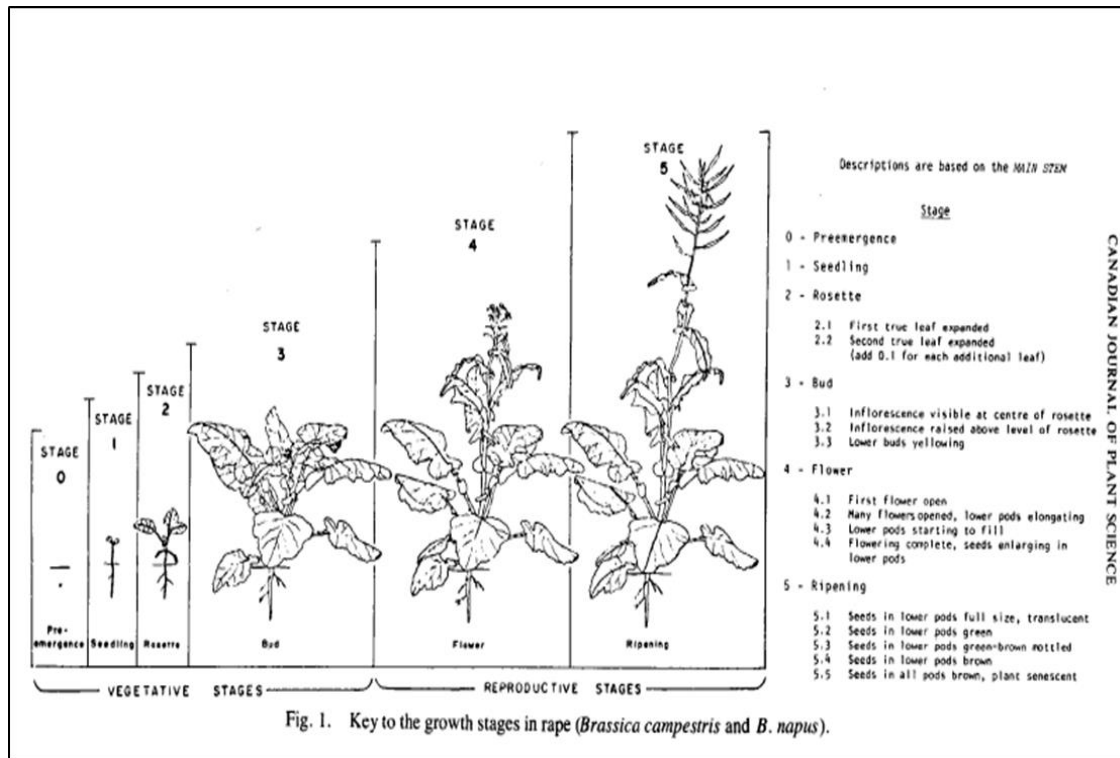
Figure. 3.1. Growth stage key for rapeseed [*B. campestris* (currently known as *B. rapa*) and *B. napus*] (source: Revised growth-stage key for *B. campestris* and *B. napus*. Figure adapted from Can. J. Pl. Sci. 55:657-658.)

Each combination of growth stages and levels of stand reduction were found within each

replication. Plants received the stand reduction treatment were removed from the soil by hand

including the root and then left the plants on top of the soil surface to desiccate and die. Five

levels of stand reduction: 0 (control), 25, 50, 75, and 90% were applied at different growth

stages. In order to administer the treatments in a consistent and accurate manner, a rectangular

1.5 m x 4.6 m pvc (12.7 mm diameter) frame was used for this study (Fig. 3.2).
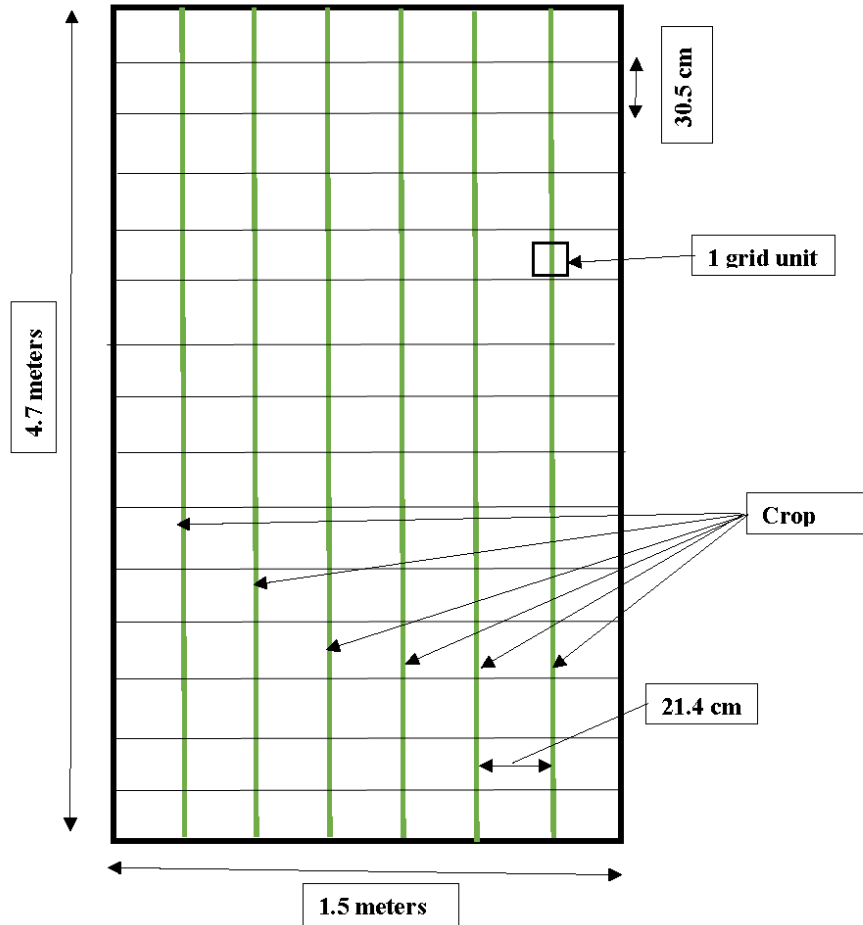
Figure. 3.2. The treatment frame perimeter was constructed of 12.7 mm diameter pvc and had 14 horizontal lines made with blank line creating 15 horizontal equidistant spaces in the grid. These equidistant spaces were the y-axis of the grid, and the horizontal crop rows were used as the x-axis in order to create grid units within the plot.

3.3.4. Field sites

The study was conducted at three different locations at North Dakota State University

Research Extension Centers (NDSU REC) at Langdon, Carrington, and Prosper, ND. The

Langdon, ND field site is located in the well-known 'canola belt' of North Dakota which is

approximately 20 miles south from the U.S.-Canadian border. The Langdon location has

multiple advantages for canola production, for instance, the soil type at this location is described

at Svea (fine-loamy, mixed Pachic Udic Haploborolls) (Soil Survey, 2018) which has a high

water holding capacity which makes it optimal for crop production. However, poor drainage is

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the limiting factor of this location. A typical frost free period in this area of ranges from 110 to 120 days. Mean annual precipitation ranges from 38 to 48 cm with the majority of that precipitation coming in the form of rain in May and through June (Soil Survey, 2018). Unlike the other two test sites, the Langdon area has historically been located in an area where canola is produced on a significant scale. In fact, average canola seed yields during the 2017 season in Langdon (Cavalier county) was approx. 2,565 kg ha^{-1} where the average yield in North Dakota is about 1,826 kg ha^{-1} (North Dakota annual bulletin, 2018). Unfortunately, the Langdon field experiment was abandoned during the 2018 season due to a clubroot *(Plasmodiophora brassicae)* infection (Fig. 3.3).

A moderate production environment such as Carrington, ND was also used in this study. Certain aspects of the Carrington field site are similar to the conditions that producers in the middle of state have to manage. The soil type at this location is primarily Emrick (coarse-loamy, mixed Pachic Udic Haploborolls) (Soil Survey, 2018), which is typically well drained, meaning that water retention within the soil is low compared to the other two sites. The typical frost free period ranges from 120 to 150 days. Mean annual precipitation ranges from 43 to 61 cm with the highest precipitation months being May and June (Soil Survey, 2018). However, total rainfall during the 2017 growing season was 34 cm which is abnormally dry for this area (NDAWN, 2018).

A less productive environment such as Prosper, ND was also used for this study. Characteristics of this location include the soil type of being primarily Perella (fine-silty, mixed, frigid Typic Haplaquolls) with some spots being Bearden (fine-silty, frigid Aeric Calciaquolls) (Soil Survey, 2018). As a result, this soil type can be described as poorly drained which combined with high average temps makes this a less than ideal location for growing canola. The

typical frost free period ranges from 110 to 160 days. Annual mean precipitation ranges from 51 to 66 cm at the research station (NDAWN, 2018).

By understanding the environmental conditions of each location, the yield and overall production potential of each respective location could be determined and would be considered representative of three different environments throughout the state.

Figure 3.3. Image of a canola plant showing symptomology of Clubroot (*Plasmodiophora brassicae*) taken on July 31st, 2018

3.3.5. Data collection and analyses

3.3.5.1. Yield

Seed yield per unit area was determined by taking the mass of the seed harvest divided by the surface area of each individual plot. From this ratio, seed yield per hectare was determined by using ratio conversion. However, flooding and other environmental factors made significant proportions of the plots in the field outliers. As a result, only three of the four replications from each treatment were used to determine the average seed yield per hectare for each environment (individual location and year). Yield data was analyzed for homogeneity of variance to determine if data sets could be combined across environments. Homogeneity of variance was determined

by dividing the environment with the highest error mean squares by the environment with lowest error mean squares. If the calculated ratio was less than 10 then data could be combined (Tabachrik and Fiddel, 2001). Data analysis was performed using PROC ANOVA in SAS 9.4.

A regression equation was developed for each growth stage using simple linear regression in order to determine seed yield reduction and economic loss due to stand reduction. Economic loss was determined by taking the regression coefficient of each growth stage times the level of stand reduction divided by 100 and then multiplied by 1,827 kg ha^{-1} (North Dakota Annual Bulletin, 2018) to determine seed yield lost in kg ha^{-1}. After which, seed yield lost in kg ha^{-1} was multiplied by \$0.39 kg^{-1} (marketing year average price) in order to determine economic loss per hectare (North Dakota Annual Bulletin, 2018).

3.3.5.2. Agronomic traits and yield components

Data on seven agronomic and four yield component traits were taken from 10 randomly selected plants per plot prior to swathing from two locations (Carrington and Prosper, ND) and two replications per treatment. However, since there was a large number of control plots, only five plants were sampled from four replicates of the control treatment per experiment for each environment. Agronomic traits include plant height, primary branches plant^{-1}, secondary branches plant^{-1}, biomass plant^{-1}, harvest index plant^{-1}, and percent oil and protein content of seed. Seed yield plant^{-1}, pods plant^{-1}, seed pod^{-1}, and 1,000 seed weight were taken for yield component traits.

Plant height was the average measured height of a plant from the apical meristem to the soil level. Sampled plants were cut with pruning shears at the soil surface and then measured.

After determining plant height, number of primary branches were counted for each sampled plant. This was accomplished by counting each branch that connected directly to the main stem of plant.

The number of secondary branches were determined by counting all of the branches that connected to the primary branches.

After, plant height, number of primary branches, and number of secondary were determined, every plant was placed in a brown paper bag labeled with plant number, location, experiment type, and treatment number. The plant samples were then dried at 70°C for 3 to 5 days.

Each of these dried plant samples were then weighed to determine biomass plant^{-1}. Pods plant^{-1} was determined by counting individual pods on each plant sampled. After the pods were counted, seed weight plant^{-1} was decided by hand threshing all the pods from a particular plant and weighing the final seed for each plant sample. Harvest index plant^{-1} was calculated by taking the seed weight plant^{-1} divided by biomass plant^{-1} and then multiplied by 100. Seeds pod^{-1} was determined for each plant sample by taking the seed weight plant^{-1} divided by 1,000 seed weight from the plot. The product was then multiplied by 1,000 in order to determine seeds plant^{-1} which was then dived by pods plant^{-1} to give seeds pod^{-1} (Dr. Burton Johnson, personal communication). 1,000 seed weight, oil, and protein content were determined by using the seed sample bags from the test plot harvests.

Weight of 1,000 was settled by taking a seed counting spatula with 100 divots. Seeds being sampled were arbitrary random by making sure that malformed seeds were not sampled. Seeds in the spatula were then weighed on a scale and data were recorded in grams; this was repeated three times for each seed sample from the test plots. All three seeds weights were

divided by 3 to express an average 100-seed weight which was then multiplied by 10 to get the final 1,000 seed weight.

Seed quality such as seed oil and protein contents was decided by taking a 20g sample from the seed sample bag and using NIR (Near Infrared Spectroscopy) to determine the total seed oil and seed protein as a percentage of the seed dry mass. All the data were then analyzed using PROC GLM in SAS 9.4. Whenever missing data was present, a single degree of freedom was subtracted.

3.4. Results and discussion

Weather data was collected from the NDAWN (https://ndawn.ndsu.nodak.edu/) station at each location. In general precipitation for the months of May to August was below normal at each location (Table 3.1).

At Carrington, total rainfall during the month of May was lower compared to normal rainfall in both the 2017 and 2018 season. Nevertheless, the moisture conditions were adequate for germination, but drought stress became evident in the seedlings during the month of May resulting in stressed seedling and uneven stands. In the 2018 season at Carrington, in addition to drought, flea beetle attack also contributed to stress the plants. In regards to Prosper location during 2017, rainfall was lower during May, but it was relativity normal during the rest of the season with the exception of high rainfall in August. During the 2018 season at Prosper, rainfall was normal or above normal. The Langdon field site during the 2017 season had a similar experience to the other two locations in that same season. Generally, the field sites in 2017 experienced low precipitation during May compared to the normal, however, the rest of the season saw an average precipitation for the remainder of the season. All of these weather patterns

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would have a direct effect on the yield potential of the test plots. Due to severe clubroot infection in Langdon site in 2018 the trial location was abandoned.

Monthly temperature were ±3°C at each location in both years (Table 3.1). Never the less, the warmer temperature in May and June of 2018 undoubtedly contributed to the drought stress noted at Carrington and Prosper.

Table 3.1. Weather data for the 2017 and 2018 growing seasons at Carrington, Prosper, and Langdon, North Dakota (NDAWN, 2018).

Environment	Month	Precipitation		Temperature			
		Rainfall	% Normal[†]	Max.	Min	Average	Normal[†]
		mm		°C			
Carrington	May	24	34	21	5	13	0
2017	June	92	96	25	11	18	0
	July	29	33	28	15	21	+1
	August	88	149	25	11	18	-2
Prosper	May	17	22	21	6	13	0
2017	June	88	88	26	12	19	0
	July	50	57	28	14	21	0
	August	53	79	25	11	18	-2
Langdon	May	25	36	18	4	11	0
2017	June	75	76	22	11	17	+1
	July	49	60	25	13	19	0
	August	48	73	24	11	17	-1
Carrington	May	32	46	24	8	16	+3
2018	June	118	123	26	14	20	+2
	July	67	78	27	13	20	-1
	August	6.1	10	27	11	19	-1
Prosper	May	53.9	70	25	9	17	+3
2018	June	79.3	79	27	14	20	+2
	July	65.3	75	27	14	20	-1
	August	78.5	118	27	12	19	-1

[†]Values are °C above or below the 1981-2010 average monthly temperature

3.4.1. Seed yield

Analysis of variance (ANOVA) indicated a significant main effect influence on seed yield for growth stage ($P<0.01$), levels of stand reduction ($P<0.01$), interaction between environment and growth stage ($P<0.05$), and interaction between environment and levels of stand reduction ($P<0.01$) (Table 3.2).

Table 3.2. Sources of variation (SOV), degrees of freedom (df), and mean squares for evaluated traits combined across five environments (Env) during 2017 and 2018.

SOV	df	Seed yield	df	1,000 seed wt	df	Protein %	Oil %
Env	4	15109283.6	4	6.06	4	69.6	122.4
Rep(Env)	10	133782.4	10	0.05	10	3.2	2.2
Growth stage (G)	3	8411844.5**	3	1.28**	3	5.6	1.1
Env X G	12	662997.3*	12	0.11**	12	5.1**	4.7
Reduction (R)	4	6875994.9**	4	1.21	4	7.1	14.8
Env x R	16	1180254.8**	16	0.00	15	5.1**	4.7
G x R	12	150329.6	12	0.28	12	4.3**	4.2
Env x G x R	48	264672.6	44	0.00	43	1.5	2.9
Error	190	335063.4	167	0.03	159	1.8	2.9
Total	299		272		262		
CV%		35.4		4.7		5.1	4.2

* and ** indicates a significance at an alpha of 0.05 and 0.01, respectively.

In regards to growth stages, it was observed that stand reduction resulted in an increasing yield loss as growth stage progressed to maturity. For example, when averaged across levels of stand reduction, the seed yield decreased by 21, 21, 28, and 46% at V4-5, bolting, 50% flower, and 90% flower, respectively (Table 3.3). Since, stand reduction occurred at later growth stages, the time frame remaining in the season was shorter compared to earlier growth stages. As a result, surviving plants had less time to take advantage of growth factors such as sunlight, nutrients, space, and soil moisture resulting in a reduced ability to compensate the seed yield.

As for the environment by growth stage interaction, it was observed that at seed yield decreased as growth stage increased for all environments. However, seed yield at both the

Prosper and Carrington locations during the 2017 season field sites tended to have lower seed

yield. The reason for these lower yields could be the result of lower precipitation observed

during the 2017 season at almost every locations with the exception of Langdon.

Table 3.3. Seed yield at four growth stages and five levels of stand reduction averaged across three replications and five North Dakota environments during 2017 and 2018.

| Stand reduction | Growth stages | | | | Means |
	V4-5	Bolting	50% flower	90% flower	
%	kg ha^{-1}				
0	2259	2406	2464	2092	2305
25	2030	2211	1958	1650	1962
50	2266	2027	1652	1199	1786
75	1341	1584	1457	894	1319
90	1244	861	732	418	814
Means	1828	1818	1653	1250	
LSD (0.05)‡			272		
LSD (0.05)†			216		

‡LSD value for comparing means over growth stages which have different levels of stand reduction.
†LSD value for comparing means over stand reduction with different growth stages.

A general trend observed was that seed yield reduction increased as growth stage and/or

levels of stand reduction increased. At stand reduction levels of 25, 50, 75, and 90%, the seed

yields were reduced by 15, 23, 43, and 65% when averaged across all growth stages and

compared to the control, respectively (Table 3.3). Probably, when the levels of stand reduction

were increased the number of surviving plants were decreased resulting in less plants to

contribute to the final reduced yield.

In regards to the environment by level of stand reduction interaction, it was observed that

yields decreased as levels of stand reduction increased for all locations. However, seed yield

tended to be higher at the Carrington location during the 2018 season. It is though that the reason

for this observation could be due to the high amount of rainfall during the month of June at

Carrington resulting in greater growth potential of surviving plants.

The interaction of growth stage by stand reduction underwent regression analysis for seed yield and a regression equation was developed for each growth stage: V4-5 (3.1), bolting (3.2), 50% flower (3.3), and 90% flower (3.4). The following equations were developed from the regression analysis:

$$V4 - 5: Y = -0.49X \qquad\qquad r^2 = 0.73 \qquad\qquad (3.1)$$

$$\text{Bolting: } Y = -0.61X \qquad\qquad r^2 = 0.86 \qquad\qquad (3.2)$$

$$50\% \text{ flower: } Y = -0.69X \qquad\qquad r^2 = 0.93 \qquad\qquad (3.3)$$

$$90\% \text{ flower: } Y = -0.84X \qquad\qquad r^2 = 0.99 \qquad\qquad (3.4)$$

In the regression equation, Y is the percent reduction in seed yield and 'X' is the levels of stand reduction in percent. These equations can predict the seed yield reduction expected from a stand reduction event at a levels of intensity from 0 to 90% at the V4-5, bolting, 50% flower, and 90% flower growth stages. For every advance in growth stage, the regression coefficient increased indicated that seed yield reduction became more severe with every increase stand reduction and growth stage. Additionally, the coefficient of determination increased with every increase in growth indicated that model would explain more of the observed variation.

When examining the economic impact of stand reduction on seed yield, it can be observed that economic losses in seed yield per hectare increase as both growth stage and level of stand reduction increased. In considering that any economic loss of \$125.00 ha^{-1} or greater was significant, the V4-5, bolting, and 50% flowering growth stages experienced significant economic losses at 50, 75, and 90% stand reduction. The 90% flowering growth stage experienced significant economic losses at 25, 50, 75, and 90% stand reduction (Table 3.4)

Table 3.4. Economic loss in U.S. dollars per hectare at four growth stages and four levels of stand reduction.

Stand reduction	Growth stages			
	V4-5	Bolting	50% flower	90% flower
%	--$ ha^{-1}--			
25	-86	-108	-122	-148
50	-173	-215	-243	-296
75	-259	-323	-365	-444
90	-311	-387	-438	-533
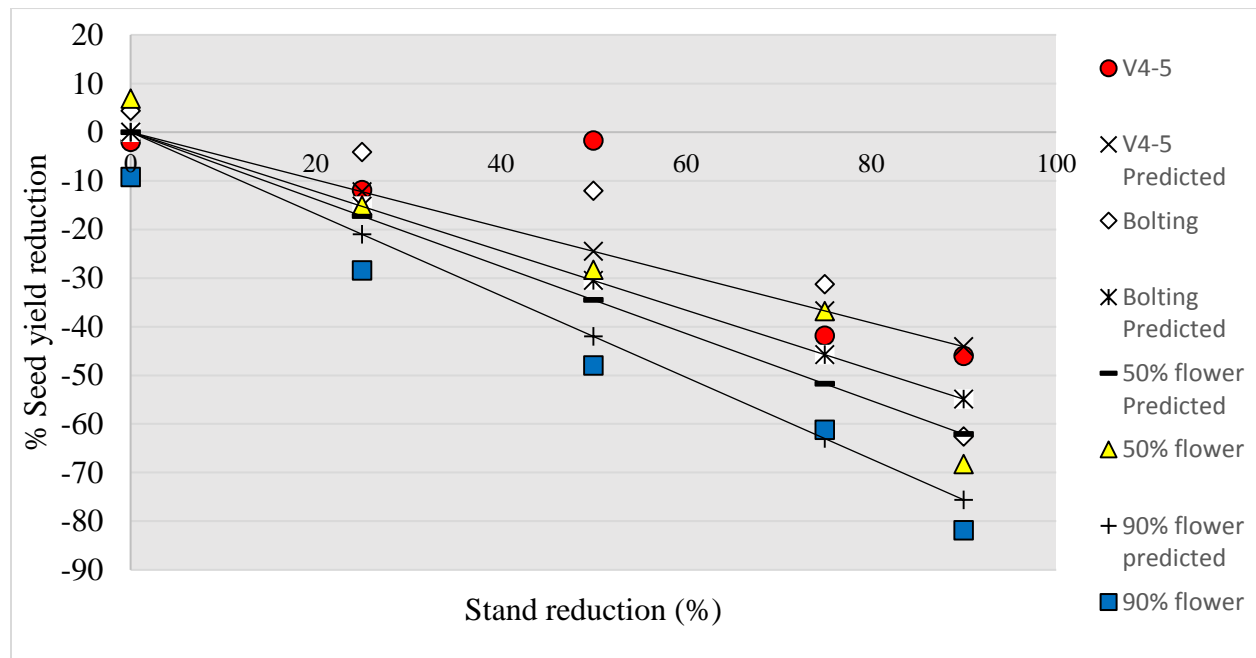
Figure 3.4. Regression analysis of predicted and observed values for canola yield at four growth stages and five levels of stand reduction averaged across five North Dakota environments during 2017 and 2018.

3.4.2. Yield component: 1,000 seed weight

ANOVA using PROC GLM indicated a significant main effect for growth stage ($P<0.01$) and the interaction between environment and growth stage ($P<0.01$).

In the case of the effect of growth stages on 1,000 seed weight, it was observed that stand reduction at maturity resulted in an increased 1,000 seed weight. For instance, 1,000 seed weight was increased by 0, 3.5, 6.7, and 9.7% at V4-5, bolting, 50% flower, and 90% flower growth

stages, respectively (Table 3.5). A possible explanation for this trend could be that inducing

stress at later growth stages.

Table 3.5. 1,000 seed wt at four growth stages and five levels of stand reduction averaged across three replications and five North Dakota environments during 2017 and 2018.

Stand reduction	Growth stages			
	V4-5	Bolting	50% flower	90% flower
%	--g/1,000 seed--			
0	3.63	3.75	3.74	3.70
25	3.73	3.68	3.79	3.87
50	3.79	3.75	3.95	4.02
75	3.63	3.92	4.01	4.32
90	3.70	4.11	4.31	4.42
Means	3.70	3.84	3.96	4.07
LSD (0.05)†		0.15		

†LSD value for comparing means over stand reduction with different growth stages.

In regards to the environment by growth stage interaction, it was observed that the

Prosper 2017 environment tended to lower seed yield across all growth stages compared the

other environments. This could be the result of the abnormally dry conditions and higher

temperatures at the Prosper location resulting in higher flower abortion resulting in less seed per

plant. As a result plants would produce less seed per plant and more resources would be

allocated by the plant to the seed.

3.4.3. Protein content in seed

ANOVA also indicated a non-significant main effect for growth stage and levels of stand

reduction on seed protein content. However, ANOVA also indicated a significant effect for the

growth stage by stand reduction interaction ($P<0.01$), environment by growth stage interaction

($P<0.01$), and environment by levels of stand reduction interaction ($P<0.01$) on seed protein

content (Table 3.2).

In regards to the environment by growth stages interaction, a general trend that observed

was more variation amounts the growth stages at Langdon during the 2017 season. It is possible

that the optimal growing conditions at Langdon could be influenced by the plants ability to recover from stand reduction.

Generally, seed protein content increased as both growth stages and levels of stand reduction increased. The greatest increase in seed protein content was observed at 90% stand reduction at 50% flower and 90% flower growth stages resulting in a 1.4 and 1.2% increase, respectively (Table 3.6). A possible explanation for this trend could be in part due to the increase biomass plant^{-1} resulting from 90% stand reduction. During leaf senescence, most of the protein in the biomass (mostly rubisco) is stored in the seeds which accounts for the majority of the protein in the seed.

As for the environment by levels of stand reduction interaction, it was observed that the protein content in seed decreased as levels of stand reduction increased. However, the Prosper 2017 environment had lower protein levels compared to the other environments. It is possible that this was due to the drought stress during the 2017 season.

Table 3.6. Seed protein content at four growth stages and five levels of stand reduction averaged across three replications and five North Dakota environments during 2017 and 2018.

	Growth stages			
Stand reduction	V4-5	Bolting	50% flower	90% flower
%	--% of seed protein--			
0	26.7	26.1	26.2	25.8
25	25.6	25.6	25.7	26.0
50	25.8	26.2	26.1	27.2
75	25.7	26.0	27.1	26.8
90	25.6	27.1	27.6	27.4
LSD (0.05)‡		0.89		

‡LSD value for comparing means with different growth stages and levels of stand reduction.

3.4.4. Plant height

ANOVA indicated a significant main effect for levels of stand reduction ($P<0.05$) and growth stage by levels of stand reduction interaction ($P<0.05$) on plant height (Table 3.7).

Table 3.7. Sources of variation (SOV), degrees of freedom (df), and mean squares for evaluated traits combined across four environments (Env) during 2017 and 2018.

SOV	df	Plant height	Prim. branch plant^{-1}	Sec. branch plant^{-1}	Biomass plant^{-1}	Plant yield	Pods plant^{-1}	Seeds pod^{-1}	Harvest index
Env.	3	5591.5	16.2	37.5	2821.8	431.3	54080.3	161.3	95.3
Rep(Env)	4	59.7	0.4	1.5	20.4	3.3	828.0	1.1	14.1
Growth stage (G)	3	59	1.9*	13.6	158.4	32.6	7872.1*	4.5	293.8**
Env x G	9	22.1	0.5*	4.8**	141.0**	17.6**	2237.5*	14.3**	33.7**
Reduction (R)	4	161.8*	7.9**	81.1**	2435.9**	320.6**	44373.1**	24.5	203.6**
Env x R	12	50.0	0.4*	2.3	154.6**	28.3**	2531.3**	8.8**	21.8*
G x R	12	45.9*	0.5	2.9	48.2	9.7	1841.0	7.1*	55.7**
Env x G x R	36	20.9	0.4*	2.6	67.9*	9.1**	1383.9*	3.0	10.1
Error	76	27.3	0.2	1.7	41.4	5.6	860.0	2.5	11.5
Total	159								
CV%		4.6	10.0	32.9	23.3	24.9	19.3	10.3	6.4

* and ** indicates a significance at an alpha of 0.05 and 0.01, respectively.

In considering of the levels of stand reduction, there was no significant difference was observed for plant height at 25, 50, and 75% stand reduction from control. However, at 90% stand reduction, the plant height significantly reduced by 8.6% from control (Table 3.8). Teigen and Vorst (1975) noted a similar trend in a stand reduction and defoliation study on soybean. During this study, soybean plots were subjected to two levels of stand reduction (0, 25, and 50%) at two growth stages (V7 and R3). They reported that the plant height decreased by 5 and 10% at V7 growth stage, and by 6 and 8% at R3 growth stages across 25 and 50% stand reduction levels, respectively. Our finding showed an agreement with Teigen and Vorst (1975) that the plant height in canola was also the lowest at the highest levels of stand reduction. In the case of a stand reduction event, plant height is effected by the levels of stand reduction rather than the stage at which the stand reduction event took place. A reason for this trend is partly due to the lack of interplant competition resulting in the surviving plants growing out horizontally rather than vertically.

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As for the growth stage by stand reduction interaction, the shortest plants were observed at the bolting growth stage at 90% stand reduction and the reason for this is unknown (Table 3.8). A common trend observed was that plant height tended to decrease as level of stand reduction and growth stages increased. However, this trend was not found to be true with the 90% flower growth stages. A possible explanation could be that plants have already completed most of their vertical growth by the time that stand reduction took place at 90% flower resulting in no height change.

Table 3.8. Plant height at four growth stages and five levels of stand reduction averaged across two replications and four North Dakota environments during 2017 and 2018.

Stand reduction	Growth stages				Mean
	V4-5	Bolting	50% flower	90% flower	
%	---cm---				
0	116	116	116	116	116
25	118	118	116	114	117
50	114	111	114	118	114
75	116	114	115	115	115
90	111	106	110	117	111
LSD (0.05)ǂ			3.9		
LSD (0.05)‡			4.6		

ǂLSD value for comparing means over growth stages which have different levels of stand reduction.
‡LSD value for comparing means with different growth stages and levels of stand reduction.

3.4.5. Primary branches plant^{-1}

ANOVA indicated a significant main effect for growth stage ($P<0.05$), level of stand reduction ($P<0.01$), growth stage by levels of stand reduction interaction ($P<0.05$), and the interaction between environment by growth stage by levels of stand reduction ($P<0.05$) (Table 3.7).

In regards to the growth stages, the increase in number of primary branches was lowest when treated at the last growth stage (90% flower). At V4-5, bolting, 50% flower, and 90% flower growth stages the number of branches increased by 18, 18, 18, and 5%, respectively (Table 3.9). Plants treated at 90% flower produce less primary branches compared to the other growth stage, because there was less time in the season for plants treated at this stage to compensate for stand reduction.

As for the interaction between environment and growth stage, primary branches plant^{-1} decreased as growth stages increased for all environments. However, primary branches plant^{-1} were higher at the 2018 Carrington environment across all growth stages with the exception of 90% flower. A possible explanation for this could be the above normal rainfall recorder during the month of June (Table 3.1).

Table 3.9. Primary branches plant^{-1} at four growth stages and five levels of stand reduction averaged across two replications and four North Dakota environments during 2017 and 2018.

Stand reduction	Growth stages				Means
	V4-5	Bolting	50% flower	90% flower	
%	Primary branches plant^{-1}				
0	4.0	4.0	4.0	4.0	4.0
25	4.0	4.1	4.4	4.1	4.2
50	4.6	4.9	4.6	4.1	4.6
75	5.3	5.0	5.2	4.1	4.9
90	5.4	5.3	5.2	4.7	5.2
Means	4.7	4.7	4.7	4.2	
LSD (0.05)‡			0.4		
LSD (0.05)†			0.3		

‡LSD value for comparing means over growth stages which have different levels of stand reduction.
†LSD value for comparing means over stand reduction with different growth stages.

As for the effect of stand reduction, a trend of increase of number of primary branches was observed. At 25, 50, 75, and 90% levels of stand reductions the number of primary branches were increased by 5, 15, 23, and 30%, respectively (Table 3.9). Plants treated with higher levels of stand reduction i.e. less plant in the plot, generally have greater accessibility to water, nutrients, and space may resulted more primary branches per plant. McGregor (1987) conducted a similar experiment in canola to access the effect of plant density on the seed yield and other agronomic traits. He reported that the stand densities of 21.1, 7.2, and 3.6 plants m^{-2}, experienced an increase of 143, 234, and 563% of primary branched on canola plant.

In regards to the environment by level of stand reduction interaction, primary branches plant^{-1} increased as the level of stand reduction increased. The Carrington 2018 environment had a higher primary branches plant^{-1}, but branches still increased as level of stand reduction increased. As mention previously, it is possible that the excess moisture during the month of June could have result in an increase in primary branches plant^{-1} due to the greater availability of soil moisture.

As for the interaction of environment by growth stage by levels of stand reduction, it was observed that primary branches plant^{-1} increased as levels of stand reduction increased and decreased as growth stages increased. This trend was observed at all environment but primary branches plant^{-1} tended to be higher at the Carrington 2018 environment.

3.4.6. Secondary branches plant^{-1}

ANOVA indicated a significant interaction for environment by growth stage ($P<0.01$) and main effect for levels of stand reduction ($P<0.01$) (Table 3.7).

In regards to the environment by growth stage interaction, it was observed that secondary branches plant^{-} decreased as growth stages increased and the environment with the lowest

secondary branches plant^{-1} were at observed at Carrington during the 2017 season. A possible

explanation could be that abnormally dry conditions during the 2017 season could have result in

restricted growth due to the limited soil moisture.

A substantial increase of secondary branches was observed with the increase of levels of

stand reduction. At 25, 50, 75, and 90% levels of stand reduction, the secondary branches were

increased by 21, 50, 100, and 163%, respectively (Table 3.10). It is assumed that as the levels of

stand reduction increased the surviving plants would have greater access to growth factors such

as nutrients, space, water, and sunlight resulted in greater biomass growth such as secondary

branches.

Table 3.10. Secondary branches plant^{-1} at four growth stages and five levels of stand reduction
averaged across two replication and four North Dakota environments during 2017 and 2018.

Stand reduction	Growth stages				Means
	V4-5	Bolting	50% flower	90% flower	
%	Secondary branches plant^{-1}				
0	2.4	2.4	2.4	2.4	2.4
25	2.9	2.9	3.2	2.5	2.9
50	3.5	4.6	3.1	3.2	3.6
75	5.4	5.5	4.8	3.6	4.8
90	6.8	7.9	5.8	4.7	6.3
LSD (0.05)‡			1.1		

‡LSD value for comparing means over growth stages which have different levels of stand
reduction.

3.4.7. Biomass plant^{-1}

ANOVA indicated a significant interaction for the environment by growth stage

interaction ($P<0.01$), levels of stand reduction ($P<0.01$), environment by levels of stand

reduction ($P<0.01$), and the environment by growth stage by levels of stand reduction ($P<0.05$)

(Table 3.7).

In regards to the environment by growth stage interaction, biomass plant^{-1} decreased as growth stage increased for all environments. However, the lowest biomass plant^{-1} were observed at the Carrington 2017 environment at the 90% flowering growth stage of treatment. Dry conditions during the 2017 season could have resulted in a decrease in biomass.

In this study it has been identified that the plant biomass was increased by the increasing stand reduction. At 25, 50, 75, and 90% levels of stand reductions the plant biomass were increases by 23, 44, 78, and 124%, respectively (Table 3.11). Probably, less plant competition for growth factors such as light, space, nutrients, and soil moisture resulted the increased plant growth. A similar trend was reported by McGregor (1987) on the development of canola related to stand reduction. In that study, the canola stands were 200, 21.7, and 7.2 plants m^{-2} and plants were sampled over the course of 100 days at 20 day intervals. It was reported that as plant densities decreased the dry weight per plant increased.

As for the environment by levels of stand reduction interaction, it was observed that the biomass increased as level of stand reduction increased, and the greatest increases in biomass plant^{-1} was at the 2018 Carrington environment. However, the 2017 Carrington environment tended to have the lowest biomass plant^{-1} compared to the other three environments. A possible explanation for these different responses at the same location could be due to the abnormally dry conditions recorded at Carrington in 2017, and the above normal rainfall during the month of June at Carrington in 2018.

Lastly, when examining the environment by growth stage by levels of stand reduction interaction, biomass plant^{-1} decreased as growth stages increased and increased as levels of stand reduction increased at all environments. The greatest increase in biomass plant^{-1} was observed at the bolting growth stage at 90% stand reduction at 2018 Carrington environment. Again, a

possible explanation for this observation could have been the above average rainfall at Carrington during the month of June in 2018.

Table 3.11. Biomass plant[-1] at four growth stages and five levels of stand reduction averaged across two replications and four North Dakota environments during 2017 and 2018.

Stand reduction	Growth stages				Means
	V4-5	Bolting	50% flower	90% flower	
%	g plant[-1]				
0	18	18	18	18	18.0
25	21	22	24	22	22.3
50	23	30	27	25	26.3
75	32	32	36	27	31.8
90	38	47	40	36	40.3
LSD (0.05)‡			6.8		

‡LDS value for comparing the means at different stand reduction levels within the same growth stage.

3.4.8. Yield component: seed yield plant[-1]

ANOVA indicated a non-significant main effect for growth stages, and the growth stages by the levels of stand reduction interaction on seed yield plant[-1]. However, the environment by growth stage interaction ($P<0.01$), levels of stand reduction ($P<0.01$), environment by levels of stand reduction interaction ($P<0.01$), and environment by growth stage by levels of stand reduction interaction ($P<0.01$) did have a significant effect on seed yield plant[-1] (Table 3.7).

With regards to the environment by growth stage interaction, see yield plant[-1] decreased as growth stages increased. However amongst the environments, the Carrington 2017 environment tended to have the lowest seed yield plant[-1] and 2018 Carrington tended to have the highest seed yield plant[-1]. It is thought that seed yield plant[-1] were lower at the Carrington 2017 environment could be the result of the lack of soil moisture needed to aid in compensation.

Increased levels of stand reduction resulted in an increased seed yield plant[-1]. For instance, when averaged across the growth stages, the seed yield plant[-1] changed by 86, 102, 124, and 159% at stand reduction levels of 25, 50, 75, and 90%, respectively (Table 3.12). Burmood

and Fehr (1973) reported a similar trend in soybean. In their study, two soybean cultivars were subjected to three levels of stand reduction (0, 25, and 50%) at three growth stages (first trifoliate, five to six trifoliate, and nine to ten trifoliate leaf stage) and two row spacing's (50 and 100cm). The study showed that an increase in stand reduction resulted in greater seed yield per plant. For example, when examining one cultivar (Hawkeye at 100cm row width) at the first trifoliate growth stages, seed yield per plant changed by 0, 32, and 100% at stand reduction levels of 0, 25, and 50%, respectively. The higher levels of stand reduction means the experimental plots contain less number of plants. Therefore, fewer plants in a plot will have access to more nutrients, space, water, sunlight etc. those may trigger to produce more seed yield plant^{-1}.

As for the environment by levels of stand reduction, seed yield plant^{-1} increased as levels of stand reduction increased. The 2018 Carrington environment had the highest increase in seed yield plant^{-1} as levels of stand reduction increased. However, the Carrington 2017 location had the lowest increase in seed yield plant^{-1} as levels of stand reduction increased. Again, it is thought that the reason for this trend could be the lack of soil moisture resulting from lower rainfall.

Seed yield plant^{-1} decreased as growth stages increased, and increased when levels of stand reduction increased. However, the greatest increase in seed yield plant^{-1} was observed at the bolting growth stage at 90% stand reduction at Carrington in 2018. It is possible that more favorable environmental conditions in the 2018 season as a whole could have resulted in the higher seed yield plant^{-1}.

Table 3.12. Seed yield plant^{-1} at four growth stages and five levels of stand reduction averaged across two replications and four North Dakota environments during 2017 and 2018.

Stand reduction	Growth stages				Means
	V4-5	Bolting	50% flower	90% flower	
%	g plant^{-1}				
0	8.8	8.8	8.8	8.8	8.8
25	7.1	7.4	8.4	7.7	7.6
50	7.6	10.9	9.3	8.3	9.0
75	10.9	11.0	12.8	9.1	11.0
90	13.0	16.7	14.5	11.9	14.0
LSD (0.05)‡			2.9		

‡LDS value for comparing the means at different stand reduction levels within the same growth stage.

3.4.9. Yield component: pods plant^{-1}

ANOVA indicated a non-significant main effect for the growth stage by levels of stand reduction interaction on mean pods per plant. However, growths stage of treatment ($P<0.05$), environment by growth stage interaction ($P<0.05$), levels of stand reduction ($P<0.01$), environment by levels of stand reduction interaction ($P<0.01$), and environment by growth stage by levels of stand reduction ($P<0.05$) did have a significant effect on the mean number of pods per plant (Table 3.7). A general trend of increased pods per plant with increased stand reductions and advanced growth stages were observed.

In considering the growth stages, no significant difference for number of pods per plant was observed between V4-5, bolting, and 50% flower stages. However, compared to the control, pod plant^{-1} increased by 36, 47, 39, and 18% for V4-5, bolting, 50% flower, and 90% flower, respectively (Table 3.13). Only, the 90% flower growth stage was significantly different from the other growth stages in which it produce fewer pods plant^{-1}. A possible explanation for this observation is that plants underwent a stand reduction event at a later growth stage did not have enough time to get recovery at the later season. The last growth stage treatment was applied during late June and early July which means that the plants typically have less time to

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compensate for stand reduction. Caviness and Miner (1962) reported a similar trend in soybean in which the decrease in number of pods per plant was greater two weeks after flowering. This indicated that after flowering, plants tend to have less ability to develop pods per plant as a means of compensating for stand reduction. Additionally, Teigin and Vorst (1975) reported an identical trend in soybean that stand reduction administered at an earlier growth stage (V7) tended to result in more pods per plant. On the other hand, pods per plant decreased as stand reduction was administered at later maturities (R3). Both of these studies highlight the trend that stand reduction at later maturity will resulted in lower pods per plant and less seed yield per plot.

As for the environment by growth stage interaction, the increase in pods plant^{-1} was lowest at the 90% flowering growth stage for all environments. However, the 2017 Carrington location tended to produce less pods plant^{-1} compared to the other three locations. It is possible that the abnormally dry conditions in 2017 could have resulted in stressed plants produce less pods plant^{-1}.

In regard to the effect of stand reduction, number of pods per plant increased with increasing levels of stand reduction. At 25, 50, 75, and 90% stand reductions the number of pods per plant increased by 11, 31, 53, and 82%, respectively (Table 3.13). It is assume that, plants at high levels of stand reduction are able to take advantage of greater accessibility to nutrients, moisture, and sunlight resulting in higher pods per plant. Angadi et al. (2003) conducted a similar experiment in canola and observed a similar effect of stand reduction on pods per plant. In that study, plant stands were 80 (control), 40 (50% stand), 20 (25% stand), 10 (12.5% stand), and 5 (6.25% stand) plants m^{-2} during the early spring seeding. They reported that the pods per plant were increased by 28, 97, 181, and 358% across stand reduction levels of 50, 25, 12.5, and 6.25%, respectively. The reason for this is that surviving plants in plots with high levels of stand

reduction had greater access to key resources to promote growth while lacking high levels of interplant competition.

In considering the environment by levels of stand reduction interaction, pods plant[-1] increased as levels of stand reduction increased, but the 2017 Carrington environment tended to produce less pods plant[-1] compared to the other three environments. Additionally, pods plant[-1] tended to be higher at Carrington in 2018. Again, it is thought that these differences in environments could be explained the variability in precipitation witnessed in both seasons.

As for the environment by growth stage by levels of stand reduction interaction, pods plant[-1] decreased as growth stages increased and increased as levels of stand reduction increased at all environments. However, pods plant[-1] tended to be lower at Carrington in 2017, and higher at Carrington in 2018.

Table 3.13. Pods plant[-1] at four growth stages and five levels of stand reduction averaged across two replications and four North Dakota environments during 2017 and 2018.

| Stand Reduction | Growth stages | | | | Means |
	V4-5	Bolting	50% flower	90% flower	
%	Pods plant[-1]				
0	113	113	113	113	113
25	120	126	138	116	125
50	143	164	151	131	147
75	183	181	188	137	172
90	212	245	197	167	205
Means	154	166	157	133	
LSD (0.05)‡	27.4				
LSD (0.05)†	23.9				

‡LDS value for comparing the means at different stand reduction levels within the same growth stage.
†LSD value comparing the means at different growth stages within the same levels of stand reduction.

3.4.10. Yield component: seeds pod[-1]

ANOVA indicated a non-significant main effect for growth stage and level of stand reduction on seeds pod[-1] (Table 3.7). However, ANOVA did indicated a significant effect for the

environment by growth stage ($P<0.01$), environment by levels of stand reduction ($P<0.01$), and growth stage by level of stand reduction interaction ($P<0.05$) on seeds pod[-1].

In considering the environment by growth stage interaction, seeds pod[-1] decreased as growth stages increased for both environments in the 2017 season. However, both environments during the 2018 season observed a considerable increase in seed pod[-1] as growth stages increased. It is possible that the drier conditions during the 2017 season could have resulted in plants being less capable to producing more seeds pod[-1]. However, precipitation during the 2018 season was relatively normal resulting in an increase in seeds pod[-1] as growth stages increased.

In respect of the growth stage by stand reduction interaction, seeds pod[-1] were the highest at the 50% stand reduction during the bolting growth stage. Seeds pod[-1] increased at 75 and 90% stand reduction during V4-5, at 50, 75, and during bolting at 25, 50, 75, and 90% stand reduction during 50% flower, and at 25 and 90% stand reduction during 90% flower (Table 3.14). A possible explanation for these trend could be that as maturity and level of stand reduction increased plants tended to have less seed yield plant[-1] resulting in the plants producing heavier seed in order to compensate for the yield loss.

As for the environment by levels of stand reduction interaction, seeds pod[-1] increased as levels of stand reduction increased. However, the greatest observed increase in seeds pod[-1] was observed during the 2018 season at Carrington which would be the result of more favorable environmental conditions such as favorable rainfall.

Table 3.14. Seeds pod^{-1} at four growth stages and five levels of stand reduction averaged across two replications and four North Dakota environments during 2017 and 2018.

Stand reduction	Growth stage			
	V4-5	Bolting	50% flower	90% flower
%	Seeds pod^{-1}			
0	14.1	13.7	13.7	13.8
25	15.3	15.5	15.8	16.5
50	14.1	17.2	15.6	15.4
75	16.4	15.7	16.5	14.0
90	16.8	16.0	16.3	16.7
LSD (0.05)‡		1.8		

‡LSD value for comparing means with different growth stages and levels of stand reduction.

3.4.11. Harvest index plant^{-1}

ANOVA indicated a significant effect for growth stage ($P<0.01$), environment by growth stage ($P<0.01$), level of stand reduction ($P<0.01$), environment by levels of stand reduction ($P<0.05$), and growth stage by levels of stand reduction interaction ($P<0.05$) on mean harvest index, and non-significant for growth stages and level of stand reduction (Table 3.7).

Harvest index plant^{-1} increased as growth stage increased with the exception of 90% flower. For instance, when averaged across all levels of stem cut-off, harvest index plant^{-1} increased by 3.7, 5.7, 6.0, and 0.8% at V4-5, bolting, 50% flower, and 90% flower, respectively (Table 3.15). It is though that plant being treated at 90% flower experienced less of a decrease compared to the other growth stages due to the fact that the plant has done most of it growth by the time that treatments were administered at 90% flower.

In considering the environment by growth stage interaction, harvest index plant^{-1} decreased as growth stages increased for all environments. The greatest decrease in harvest index plant^{-1} was observed at Prosper during the 2017 season at the 90% flowering growth stage. It is thought that the Prosper 2017 season observed the greatest decrease in harvest index plant^{-1} due

to lower seasonal precipitation and hotter weather resulting in flower abortion and hence lower seed yield plant^{-1} in reference to biomass plant^{-1}.

Harvest index plant^{-1} increased as level of stand reduction increased. For example, when averaged across all growth stages, harvest index increased by 5.3, 6.2, 4.0, and 4.7% at V4-5, bolting, 50% flower, and 90% flower, respectively (Table 3.15). A possible explanation for these trends could be the result of a higher increase in seed yield plant^{-1} in respect to biomass plant^{-1} resulting in a higher harvest index plant^{-1}.

With respect to the environment by level of stand reduction interaction, harvest index plant^{-1} decreased as levels of stand reduction increased during the 2017 season. However, during the 2018 season, harvest index plant^{-1} increased as levels of stand reduction increased. It is possible that the reason that these two season experience a different response to harvest index plant^{-1} is due to the greater availability of soil moisture in the 2018 season. As a result, plants would have a greater capacity to produce more seed yield plant^{-1} in respect to biomass plant^{-1}.

In regards to the effect of the growth stage by level of stand reduction interaction, it was observed that harvest index plant^{-1} increased during the V4-5 growth stages when treated with 90% stand reduction. Additionally, significant increases in harvest index plant^{-1} were observed during bolting at stand reduction levels of 50 and 90%. During 50% flower, stand reduction levels of 25, 50, 75, and 90% increased significantly. Lastly at the 90% flower growth stages, only 25% stand reduction had a significant increase in harvest index plant^{-1}. It is thought that harvest index plant^{-1} tended to increase 50% flower due to seed yield plant^{-1} increasing at a higher rate compared to biomass. As a result, harvest index is the proportion of seed weight in reference to total plant biomass. If seed yield plant increases while biomass remained relatively stable; it would reason that harvest index would increase.

Table 3.15. Harvest index plant^{-1} at four growth stages and five levels of stand reduction averaged across two replications and four North Dakota environments during 2017 and 2018.

Stand reduction	Growth stages				Means
	V4-5	Bolting	50% flower	90% flower	
%	Harvest index plant^{-1}				
0	32.2	32.2	32.2	32.2	32.2
25	32.9	33.0	34.7	35.0	33.9
50	32.7	36.3	34.8	33.0	34.2
75	34.1	34.0	34.7	31.1	33.5
90	35.0	34.6	34.3	31.0	33.7
Means	33.4	34.0	34.1	32.5	
LSD (0.05)ᵻ		2.5			
LSD (0.5)†		2.9			
LSD (0.05)‡		3.2			

ᵻLSD value for comparing means over growth stages which have different levels of stand reduction.
†LSD value for comparing means over stand reduction with different growth stages.
‡LSD value for comparing means with different growth stages and levels of stand reduction.

3.5. Summary

Plant injury from hail damage can be influence by many factors such as hail stone size, velocity, density, and duration. Additionally, there are various types of damage that can be manifested by a hail storm. Stand reduction was examined in this study is only one form of damage inflected by hail damage.

90% flower growth stage had the highest seed yield loss out of any of the other growth stages in the stand reduction experiment. 90% stand reduction at growth stages V4-5, bolting, 50% flower, and 90% flower resulted in seed yield losses of 46, 63, 68, and 82% when compared to the control, respectively. As the levels of stand reduction and growth stages are increased, the seed yield reduction also increased. Stand reduction at later growth stages such as 90% flower resulted in a lower capacity for surviving plants to compensate for the yield loss.

As for the economic impact of stand reduction on seed yield, economic losses per hectare increased as both growth stage and level of stand reduction increased. For instance, economic

losses per hectare were $207, $258, $292, and $355 for V4-5, bolting, 50% flower, and 90% flower growth stages, reactively (Table 3.4). As for the level of stand reduction, economic losses per hectare were $116, $232, $345, and $417 at 25, 50, 75, and 90% stand reduction when averaged across growth stages (Table 3.4).

Yield components were also evaluated to explain the seed yield response to stand reduction. Both plant biomass and seed yield increased as stand reduction level increased, but these components decreased with increasing growth stages. Yield components were based on individual plant samples taken from four environments which showed the individual plant response to stand reduction when performed at the V4-5, bolting, 50% flower, and 90% flower growth stages. Generally, as stand reduction increased, plant biomass and seed yield also increased due to greater accessibility of growth factor such as light, space, nutrients, and soil water.

Pods plant^{-1} was significantly impacted by growth stages and stand reduction. At growth stages V4-5, bolting, 50% flower, and 90% flower, number of pods plant^{-1} were 212, 245, 197, and 167 at 90% stand reduction, respectively. The recovery of plants to stand reduction became less apparent as plant reached the reproductive stages. Additionally, this indicates that pods plant^{-1} was the main yield component responsible for seed yield reduction.

Data for all yield components indicated stand reduction during the early part of the growing season had less effect on yield. On the other hand, stand reduction occurring during later part of the growing season typically resulted in greater yield reduction even at lower levels of stand reduction. The increase in pods plant^{-1} declined as the growth stage at which the stand reduction took place increased demonstrating that yield component compensation was limited with advanced maturity.

3.6. References

Angadi, S. V., H. W. Cutforth, B. G. McConkey, and Y. Gan. 2003. Yield adjustment by canola grown at different plant populations under semiarid conditions. Crop Science 43: 1358-1366.

Boone, L. M. 1974. Estimating crop losses due to hail. agricultural economics report 267, U.S. Department of Agriculture, Washington, D.C.

Burmood, D.T., and W.R. Fehr. 1973. Variety and row spacing effects on recoverability of soybeans from simulated hail injury 1. Agron. J. 65: 301-303.

Canola Council of Canada, 2017. Evaluating the stand. [Online]. Available on https://www.canolacouncil.org/canola-encyclopedia/plant-establishment/evaluating-the-stand/ (verified 1 Nov. 2019).

Caviness, C. E., and F. D. Miner. 1962. Effects of stand reduction in soybeans simulating three-cornered alfalfa hopper injury1. Agron. J. 54: 300-302.

Changnon Jr., S.A. 1972. Examples of economic losses, from hail in the United States. J. Appl. Meteorol. 11:1128-1137.

Harper, F.R., and B. Berkenkamp. 1975. Revised growth-stage key for *Brassica campestris* and *B. napus*. Can. J. Pl. Sci. 55:657-658.

McGregor, D.I. 1980. The nature of hail injury in rapeseed. Can. J. Pl. Sci. 60:1441-1449.

McGregor, D.I. 1987. Effect of plant density on development and yield of rapeseed and its significance to recovery from hail injury. Can. J. Pl. Sci. 67:43-45.

Nagaharu, U. 1935. Genome analysis in Brassica with special reference to the experimental formation of B. napus and peculiar mode of fertilization. Japan. J. Bot. 7: 389–452.

North Dakota Agricultural Weather Network, NDSU. Monthly weather data. [Online]. Available

on https://ndawn.ndsu.nodak.edu/weather-data-monthly.html (verified 1 Nov. 2018).

North Dakota Annual Bulletin, NASS, 2018. Canola acreage, yield, production, price, and value

North Dakota: 2008-2017. [Online]. Available on

https://www.nass.usda.gov/Statistics_by_State/North_Dakota/Publications/Annual_Statis

tical_Bulletin/2018/ND-Annual-Bulletin18.pdf (verified 1 Jan. 2019).

National Agricultural Statistics Services (NASS), USDA, 2018. [Online]. Available on

https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NORTH

%20DAKOTA (verified 1 Feb. 2019).

Raymer, P.L. 2002. Canola: An emerging oilseed crop. ASHS Press: 122–126.

Soil Survey Staff, NRCS, USDA. Web soil survey. [Online]. Available at

https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm (verified 1 Nov. 2018).

Tabachnick B.G. and L.S. Fidell. 2001. Using multivariate statisitcs. 4th ed. Harper Collins, New

York City, NY.

Teigen, J.R., and J.J. Vorst. 1975. Soybean response to stand reduction and defoliation 1. Agron.

J. 67: 813-816.

4. STEM CUT-OFF STUDY

4.1. Abstract

Severity of hail damage depends on developmental stages of crop, level of damage, types of damage such as stand reduction, stem cut-off, etc. The effect of stem cut-off on canola seed yield and plant performance has yet to be addressed. A simulated hail damage study was conducted in North Dakota over two years. The experiment was laid out in a randomized complete block design with a factorial arrangement with two factors, four growth stages and five levels of stem cut-off, replicated four times for each combination. Data on seed yield plot^{-1} and other yield contributing traits were taken. Seed yield was decreased at the advancement of growth stages and increment of levels of stem cut-off. A regression equation was developed from this study to estimate the yield reduction from different treatments and growth stages. Biomass plant^{-1}, seed yield plant^{-1}, pods plant^{-1}, and harvest index plant^{-1} were decreased at the levels of stem cut-off increased. Our findings of differential yield losses by stem cut-off will aid producers/adjusters more quickly and accurately assess the severity of hail damage in canola.

4.2. Introduction

The term canola is derived from "Canadian Oil Low Acid" and is a trademark of the Canadian Canola Association. In order to be a designated canola cultivar, *Brassica* oilseed cultivars need to have low erucic acid (<2%) and low glucosinolate content (less than 30 micromoles/gram) in the meal (Raymer, 2002). The most common *Brassica* species given the designation of canola is *Brassica napus* (L.). Within the United States, North Dakota is the largest producer of canola accounting for approximately 84% of all land devoted towards production and worth around $403 million dollars during the 2017 season (NASS, USDA, 2018).

In the past two decades, there has been an expansion of canola acreage in North Dakota and the United States as a whole. One reason for this increase is the relative stability and profitability of canola seed prices in comparison to the other crops. Additionally, innovations in the breeding industry such as shatter resistant canola cultivars have made canola management and harvesting more attractive to producers due to the lower risk of shattering and volunteer canola in the preceding season. Also, conservative tillage practices such as no-till or minimum tillage combined with drought/heat tolerant cultivars have resulted in increased canola production in more arid areas such as southwestern North Dakota.

Within the past few decades, southwestern North Dakota has seen an increase in land devoted towards canola production. However, the constant threat of drought and unpredictable weather patterns have been a constant production challenge to producers in this region. The National Crop Insurance Service (2018), North Dakota has reported that the highest annual crop losses due to hail damage was occurred in 2017 in the United States. In that same year, North Dakota received $45 million in crop losses due to mostly drought and hail losses (National Crop Insurance Service, 2018). Historically, most of these losses tend to be concentration around southwestern North Dakota with some of the counties having the highest insurance payouts in the United States (Miller and Fuhs, 1987). However, compared to other major crops such as maize (*Zea mays* L.) or soybeans *(Glycine max* (L.) Merril), canola has considerably less acreage in the United States resulting in little interest in hail studies. Consequently, lack of interest and funding has resulted the hail study being rarely conducted on canola.

It is critical to understand how different types of hail damage would affect the development and performance of canola plants with regards to seed yield. The objective of this

research was to access the crop damage using simulated hail damage with different levels of stem cut-off at various plant growth stages.

4.3. Materials and methods

4.3.1. Experimental design

The stem cut-off experiment was conducted using a randomized complete block design with a factorial arrangement with two factors, growth stages and levels of stem cut-off, at three locations in North Dakota in 2017 and 2018. Both of these factors were considered fixed effects, however, replication and environments (each location and year combination) were considered random effects. Each factorial combination was replicated four times at each of six environments. The plot size was 1.3 m x 4.6 m, and the seeding rate was 6 kg ha^{-1} or 1,075,000 seeds ha^{-1}. Ammonium sulfate and urea fertilizers were applied to attain a canola seed yield goal of at least 2,242 kg ha^{-1}at Carrington, 2,242 kg ha^{-1} at Prosper, and 2.802 kg ha^{-1} at Langdon. Trifluralin was used as a pre-emergence herbicide, and Glyphosate was used for post-emergence control of weeds. Initial stand establishment was determined by counting the plants in an m^2 sample frame, twice for each plot at every environment. Final crop stand was determined after harvesting by counting all of the stubble stems in a square meter sample twice per plot.

4.3.2. Plant materials

A roundup ready commercial canola hybrid 'DKL 70-10' acquired from Monsanto, West Fargo, ND was used in this study. It is one of the many commercial canola cultivars grown in North Dakota. The seeds were treated with Helix Xtra (Syngenta, USA), which is a systemic insecticide belonging to the neonicotinoid family. Primarily, this insecticide is used for the early season crucifer flea beetle (*Phyllotreta cruciferae* (Goeze)) control, but it can also be used as a fungicide against blackleg, *Alternia* and other diseases.

In both 2017 and 2018, the experiment was planted in three locations. During the 2017 season, the experiment was planted at Carrington on May 9, Prosper on May 12, and Langdon on May 19. Harvest took place on August 29 at Carrington, Prosper on September 4, and Langdon on September 13. During the 2018 season, this experiment was planted at Carrington on May 14, Langdon on May 15, and Prosper on May 22. These plots were harvested on August 29 at Carrington and September 9 at Prosper. Langdon location was abandoned due to factors discussed later.

4.3.3. Stem cut-off

The stem cut-off experiment was conducted at four different growth stages. These growth stages were consisted of 4th to 5th leaf rosette (2.4 to 2.5), bolting (3.1 to 3.2), 50% flower (3.3 to 4.1), and 90% flower (4.3 to 4.4) (Harper and Berkenkamp, 1975) (Fig. 4.1). At each of the four growth stages, five levels of stem cut-off such as 0% (control), 25, 50, 75, and 90% were used. Plants were cut at half of their height of each treatment. A frame was used to apply an accurate and consistent treatment on treated plants (Fig. 4.2).
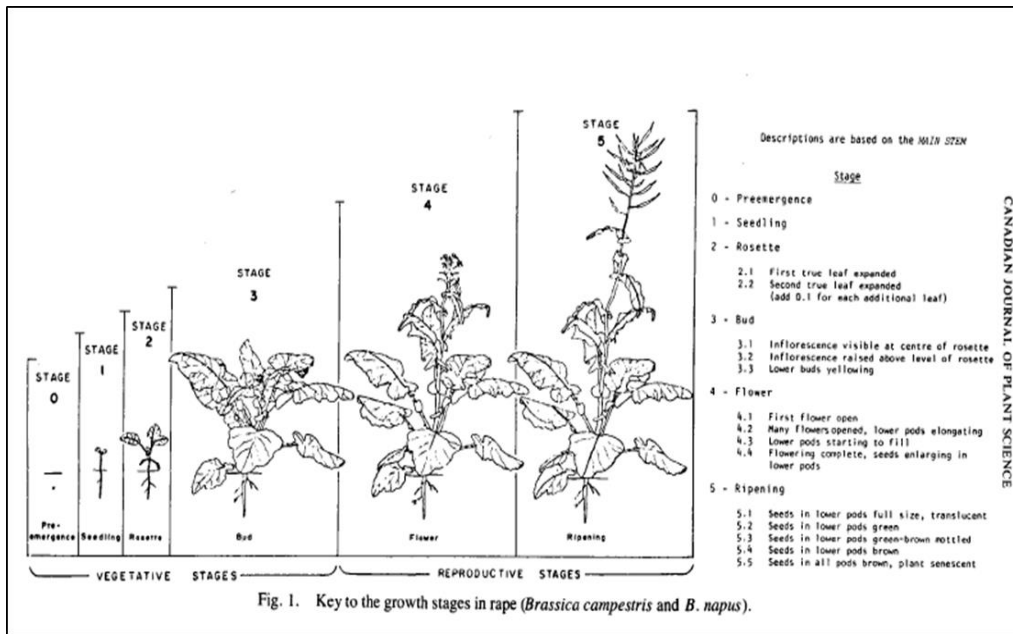
Figure 4.1. Growth stage key for rapeseed (B. campestris and B. napus) (source: Revised growth-stage key for B. campestris and B. napus. Can. J. Pl. Sci. 55:657-658.)
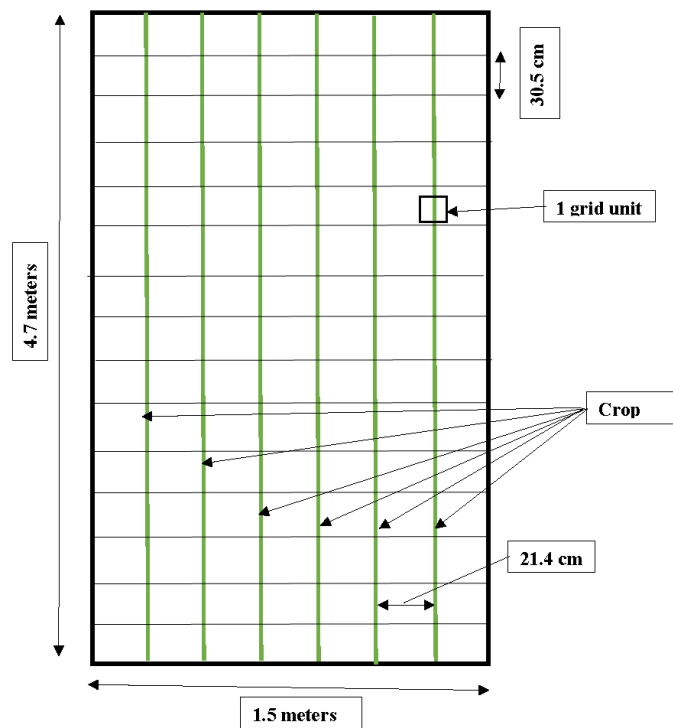
Figure 4.2. The treatment frame perimeter was constructed of 12.7 mm diameter pvc and had 14 horizontal lines made with bank line creating 15 horizontal equidistant spaces in the grid. These equidistant spaces were the y-axis of the grid, and the horizontal crop rows were used as the x-axis in order to create grid units within the plot.

4.3.4. Field sites

The experiment was conducted at North Dakota State University Research and Extension Centers at Langdon, Carrington, and Prosper, ND. Majority of canola acreage of North Dakota is located around Langdon region (Cavalier county), and therefore this site was selected for this study. The average canola seed yields during the 2017 season in Langdon area was approx. 2,565 kg ha^{-1} where the state wide average yield in North Dakota was 1,826 kg ha^{-1} (North Dakota Annual Bulletin, 2018). The soil type at this location is described at Svea (fine-loamy, mixed Pachic Udic Haploborolls) (Soil Survey, 2018), which has a high water holding capacity and optimal for crop production. However, poor drainage condition is a concern for this soil type. A typical frost free period in this area of North Dakota ranges from between 110 to 120 days. Annual precipitation ranges from 38 to 48 cm with the majority of that precipitation occurs during May and June (Soil Survey, 2018).

During the 2018 season at Langdon, a severe outbreak of clubroot *(Plasmodiophora brassicae)* resulted in the environment being abandoned (Fig. 4.3). However, it is still important that a high production environment was included in this study in order to unstand the effect of stem cut-off in this environment.

Figure 4.3. Image of a canola plant showing symptomology of Clubroot (*Plasmodiophora brassicae*) taken on July 31st, 2018.

A moderate canola production environment such as Carrington, ND, located in the middle of the state was also used in this study. The soil type at this location is primarily Emrick (coarse-loamy, mixed Pachic Udic Haploborolls) (Soil Survey, 2018), which is typically well drained, meaning that water retention within the soil is low compared to the other two sites. An average frost free period for Carrington is typically around 120 to 150 days. As for annual precipitation, most of the rainfall was received during the months of May and June with an average of 43 to 61 cm in rainfall total (Soil Survey, 2018). During the 2017 season, total rainfall was 34 cm which is abnormally dry for this area (NDAWN, 2018).

In order to have a full range of representative environments, a less productive environment such as Prosper, ND was used. The soil type of this location is primarily Perella (fine-silty, mixed, frigid Typic Haplaquolls) with some spots being Bearden (fine-silty, frigid Aeric Calciaquolls) (Soil Survey, 2018), which is poorly drained. The location has a high average temperature that makes it a poor growing region for canola. The typical frost free period

ranges from between 110 to 160 days. Annual precipitation ranges from 51 to 66 cm at the research station (Soil Survey, 2018). By understanding the environmental conditions of each location, the production potential of each location could be used to determine the effect of stem cut-off and stand reduction across the eastern portion of the state.

4.3.5. Data collection and analysis

4.3.5.1. Yield

In order to determine seed yield per unit of area, the mass of the seed harvest was divided by the surface area of each plot, and seed yield per hectare was determined by using ratio conversion. Due to variation in the field such as flooding, soil crusting, etc., there was a significant amount of variation amongst replications in the field. Therefore, in order to reduce variation, three of the four replications for each treatment were used to determine the average seed yield per hectare for each environment (individual location and year).

Before performing the combined analysis, homogeneity of variance was determined by taking the environment with the highest error mean square divided by the environment with the lowest error mean square. In the case that the calculated ratio was less than 10 then data across environments could be combined as described by Tabachrik and Fiddel (2001). PROC ANOVA using SAS 9.4 was used to perform data analysis.

4.3.5.2. Agronomic traits and yield components

Ten representative plant samples from each sampled plot before swathing the plots from two locations (Carrington and Prosper, ND) and two replications per treatment for data on seven agronomic traits and four yield components. Due to a large number of controls, five plants were sampled from four replicates of control treatments for each experiment at every environment sampled. Agronomic traits such as plant height, primary branches plant^{-1}, secondary branches

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plant^{-1}, biomass plant^{-1}, harvest index^{-1}, and percent oil and protein content of seed were taken. As for yield component traits, data was recorded for seed yield plant^{-1}, pods plant^{-1}, seeds pod^{-1}, and 1,000 seed weight.

After cutting each plant at the soil surface, plant height data was determined by measuring from the bottom of the plants to the top of the plant.

Once plant height had been determined, number of primary branches were counted. This was accomplished by counting each branch that connected to the main stem via a node.

The number of secondary branches was determined by counting every branch that stemmed off a primary branch and that did not connect directly to the main stem via a node.

After taking the data on plant height, number of primary branches, and number of secondary branches, the plant samples were dried at 70°C for 3 to 5 days. Biomass plant^{-1} was determined by weighing each plant sample after drying. After recording the data on biomass plant^{-1}, the pods plant^{-1} was determined by carefully picking and counting each pod of the dried plant sample. Once the pods were counted, the plants were crushed and threshed by hand to determine the seed yield plant^{-1}.

Seeds pod^{-1} was determined by taking the seed yield plant^{-1} divided by the 1,000 seed weight. Then the product was multiplied by 1,000 to give seeds plant^{-1}. This was then divided by the pods plant^{-1} from that treatment in order to calculate seeds pod^{-1} (Dr. Burton Johnson, personal communication).

Harvest index plant^{-1} was calculated by dividing seed yield plant^{-1} by total biomass plant^{-1} followed by a multiplication of 100.

1,000 seed weight was determined by using a seed counting spatula with 100 divots with three samples per plot. Weight of the three 100-seed samples were taken, averaged, and multiplied by 10 to get the final 1000 seed weight.

Seed oil and seed protein contents were determined by taking a 20g seed sample from each experimental plot, and analyzed using NIR (Near Infrared Spectroscopy).

Data were analyzed using PROC GLM in SAS 9.4.

4.4. Results and discussion

From each location, weather data was collected from the NDAWN stations. Generally, rainfall between the months of May to August were below normal (Table 4.1).

In the 2017 and 2018 season, Carrington experienced lower total rainfall compared to normal in the month of May. Soil moisture was adequate for germination, however, drought stress became evident during the month of May resulting in stressed plants and uneven stands. In addition to drought stress in the 2018 season, Carrington also experienced high flea beetle damage and high rainfall in the month of June resulting in soil crusting which contributed to the stressed plants.

Similarly in 2017, Prosper experienced lower than normal rainfall during May, but rainfall was relatively normal during the rest of the season with the exception of high rainfall in August. However, during the 2018 season, Prosper experienced normal or above normal rainfall throughout the season.

During the 2017 season, Langdon experienced a similar trend to the other locations in which rainfall during the month of May was generally low, but remained relatively close to normal to 70% during the remainder of the season. The Langdon field site was abandoned during the 2018 season due to clubroot *(Plasmodiophora brassicae)*.

In both the 2017 and 2018 seasons, average monthly temperature were ±3°C at each location (Table 4.1). However, the drought stressed noted at Carrington and Prosper during the 2018 season was intensified by the warmer temperatures in May and June. All of these weather patterns would have a direct effect on the yield potential of the test plots.

Table 4.1. Weather data for the 2017 and 2018 growing seasons at Carrington, Prosper, and Langdon, North Dakota (NDAWN, 2018).

Environment	Month	Precipitation		Temperature			
		Rainfall	% Normal†	Max.	Min	Average	Normal†
		mm		°C			
Carrington 2017	May	24	34	21	5	13	0
	June	92	96	25	11	18	0
	July	29	33	28	15	21	+1
	August	88	149	25	11	18	-2
Carrington 2018	May	32	46	24	8	16	+3
	June	118	123	26	14	20	+2
	July	67	78	27	13	20	-1
	August	6.1	10	27	11	19	-1
Prosper 2017	May	17	22	21	6	13	0
	June	88	88	26	12	19	0
	July	50	57	28	14	21	0
	August	53	79	25	11	18	-2
Prosper 2018	May	53.9	70	25	9	17	+3
	June	79.3	79	27	14	20	+2
	July	65.3	75	27	14	20	-1
	August	78.5	118	27	12	19	-1
Langdon 2017	May	25	36	18	4	11	0
	June	75	76	22	11	17	+1
	July	49	60	25	13	19	0
	August	48	73	24	11	17	-1

† Values are °C above or below the 1981-2010 average monthly temperatures.

4.4.1. Seed yield

Analysis of variance (ANOVA) indicated a significant main effect for growth stage ($P<0.01$), environment by growth stage interaction ($P<0.01$), environment by level of stem cut-

off ($P<0.05$), and environment by growth stage by level of stem cut-off interaction ($P<0.01$)

(Table 4.2). An inverse relationship between the treatments and seed yield was observed, where

with the increase of growth stages the seed yield was decreased (Table 4.3).

Table 4.2. Sources of variation (SOV), degrees of freedom (df), and mean squares for evaluated traits combined across five environments (Env) during 2017 and 2018.

SOV	Seed yield		1000 seed wt		Protein (%)		Oil (%)
	df	MS	df	MS	df	MS	MS
Env.	4	3927120	4	4.40	4	161.1	186.2
Rep (Env)	10	578137.9	10	0.06	10	6.5	7.5
Growth stage (G)	3	1576290**	3	0.63*	3	1.2	5.4
Env x G	12	756616**	12	0.13**	12	1.5	1.9
Stem Cut-off (C)	4	507706.5	4	0.04	4	1.9	6.0*
Env x C	16	545523.5*	16	0.04	16	0.7	1.5
G x C	12	690842.9	12	0.12*	12	2.4*	1.6
Env x G x C	48	528617.2**	47	0.05	47	1.1	1.4
Error	190	275890.8	182	4.40	176	1.5	1.8
Total	299		290		284		
CV%		18.7		5.3		4.7	3.3

* and ** indicates a significance at an alpha of 0.05 and 0.01, respectively

Compared to the other growth stages, the plots received the stem cut-off treatment at the

90% flower growth stage had a higher seed yield reduction. For instance, when averaged across

all levels of stem cut-off, the growth stages of V4-5, bolting, 50% flower, and 90% flower had an

average seed yield reduction of 6, 3, 5, and 22%, respectively (Table 4.3). Stem cut-off

administered at 90% flower resulted in the lowest yields. Probably, plants with stem cut-off after

90% flower would have less chance to generate new healthy branches or inflorences due to

exposure to high temperatures in the later season resulting in flower abortion and seed yield

reduction. Fehr et al. (1977) conducted a similar stem cut-off study on soybean. In that study,

indeterminate (grown in Iowa) and determinate (grown in Arkansas) soybeans were subjected to

100% half-plant cut-off at six growth stages (R2-R7). The indeterminate soybeans experienced a

reduction in yield of 7, 22, 38, 45, 46, and 48% across growth stages R2, R3, R4, R5, R6, and R7, respectively. These results showed an agreement with our finding in canola.

Economic losses due to seed yield losses increased as growth stages and level of stem cut-off increased. In this study, we considered any economic loss of $125 ha^{-1} or greater was considered significant. For the 50% flowering growth stages, no level of stem cut-off resulted in a significant yield loss. However, stem cut-off levels of 50, 75, and 90% resulted in significant economic losses from stem cut-off damage (Table 4.4).

In regards to the environment by growth stage interaction, seed yield decreased as growth stages increased at all environments. However, seed yields tended to be higher at all locations sampled during the 2018 season. It is possible that the dried environments during the 2017 season could have hampered the ability of plants to produce seed.

Table 4.3. Seed yield at four growth stages and five levels of stem cut-off averaged across three replications and five North Dakota environments during 2017 and 2018.

Stem cut-off	Growth stages				Means
	V4-5	Bolting	50% flower	90% flower	
%	kg ha^{-1}				
0	2512	2578	2840	2764	2673
25	2604	2669	2478	2215	2492
50	2596	2500	2443	2122	2415
75	2408	2587	2599	1763	2340
90	2441	2618	2377	1537	2243
Means	2512	2590	2547	2080	
LSD (0.05)‡	255				
LSD (0.05)†	310				

‡LSD value for comparing means over growth stages which have different levels of stem cut-off.
†LSD value for comparing means over levels of stem cut-off with different growth stages.

As for the environment by levels of stem cut-off interaction, seed yield decreases as levels of stem cut-off increased for all environments. However, seed yields tended to be higher at Carrington in 2018, and seed yields tended to be lower at Prosper during 2017. It is possible that

the favorable conditions at Carrington during the 2018 season could have resulted in greater

regrowth potential compared to the other environments.

With regards to the environment by growth stage by levels of stem cut-off, seed yield

decreased as growth stages and levels of stem cut-off increased for all environments. However,

seed yields tended to decrease by a lesser extent during the 2018 season compared to

environments in the 2017 season. A possible explanation could be the dried conditions during the

2017 season could have resulted in lower seed yields in those environments.

In order to quantify yield reduction, the interaction of the growth stages by stem cut-off

underwent for a regression analysis for seed yield, and a regression equation was developed for

each of the growth stages. However, the interaction between growth stages and levels of stem

cut-off at V4-5 and bolting growth stages could not undergo simple linear regression to develop

an equation. The reason being that seed yields between levels of stem cut-off within the same

growth stage were not significantly different from the control meaning that an equation could not

be developed to predict seed yield reduction. Therefore, the regression equations were only

developed for the 50% flower (4.1) and 90% flower (4.2) growth stages. The following equations

were developed from the regression analysis:

$$50\% \text{ flower:} Y = -0.16x \qquad\qquad r^2 = 0.77 \qquad\qquad (4.1)$$

$$90\% \text{ flower:} Y = -0.43x \qquad\qquad r^2 = 0.97 \qquad\qquad (4.2)$$

Table 4.4. Economic loss in US dollars per hectare at two growth stages and four levels of stem cut-off.

	Growth stages	
Stem cut-off	50% flower	90% flower
%	--$ ha^{-1}--	
25	-28	-76
50	-56	-152
75	-85	-227
90	-102	-273

For the regression equation, Y is the percent reduction in seed yield and 'X' is the level of stem cut-off in percent. In this study it was observed that the regression coefficient decreased as the growth stages increased (Table 4.2). A possible explanation would be that as both growth stage and levels of stem cut-off increase, the predicted seed yield will decrease in a linear fashion. It is assumed that the plants treated at later growth stages would have less ability to compensate from the damage which would ultimately reduce the seed yield of the treated plants. Similar trends have been reported in flax (Soine, 1970), peas (Miller and Muehlbauer, 1984), and soybean (Fehr et al, 1983).
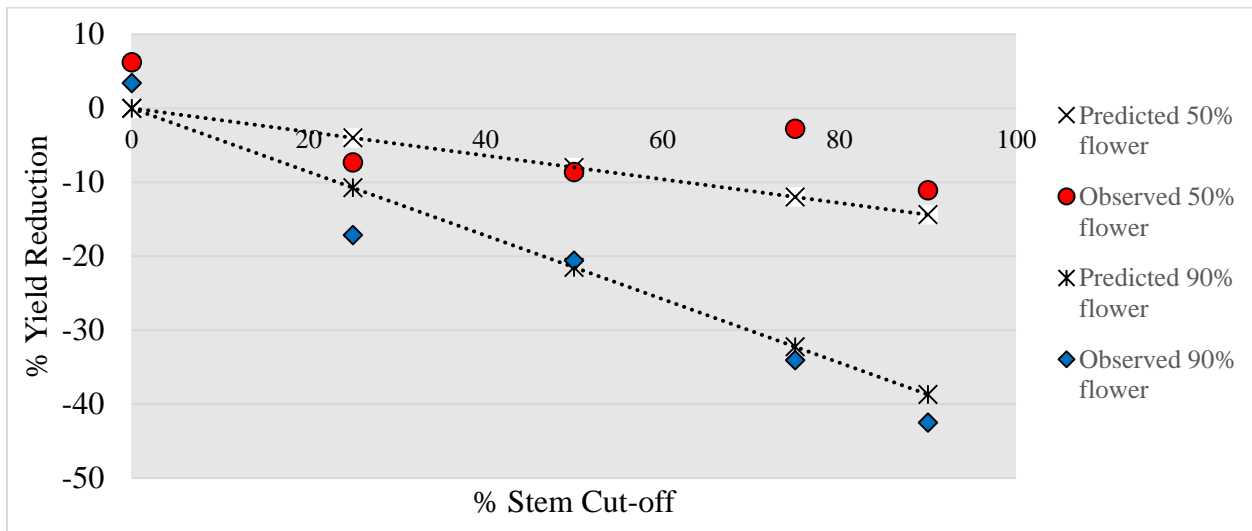
Figure 4.4. Regression analysis of predicted and observed values for yield reduction at two growth stages and five levels of stem cut-off averaged across five North Dakota environments during 2017 and 2018.

The economic impact of stem cut-off on seed yield of canola was determined to be significant when seed yield losses equated to $125 ha^{-1}. As a result, no level of stem cut-off occurred during 50% flower resulted in a significant economic loss. However, stem cut-off occurring during the 90% flowering stage was significantly different for stem cut-off levels of 50, 75, and 90% (Table 4.4).

4.4.2. Yield component: 1,000 seed weight

Thousand seed weight was directly impacted by stem cut-off. ANOVA using PROC GLM indicated a significant main effect for growth stage ($P<0.05$), the environment by growth stage interaction ($P<0.01$), and the growth stage by stem cut-off interaction ($P<0.05$) on 1,000 seed weight (Table 4.2).

Plants treated at later growth stages tended to have higher 1,000 seed weight. For instance, when averaged across all levels of stem cut-off, it was observed that 1,000 seed weight increased by 0, 3.5, 6.7, and 9.7% for growth stages V4-5, bolting, 50% flower, and 90% flower, respectively (Table 4.5). We have seen an inverse relationship between seed yield and seed weight. Here the seed yield decreased and seed weight increased when plants were treated at later growth stage. It is assumed that whenever seed yields decreased, the plants compensated by storing most of the carbon from photosynthesis and protein from leaf senescence into the remaining seeds resulting in heavier seed weight. Fehr et al. (1977) reported a similar trend in a stem cut-off study conducted on indeterminate soybeans. They observed that the seed weight (g/100 seeds) tended to increase when subjected to 100% stem cut-off. However, this trend was only apparent in growth stages before physiological maturity.

In regards to the environment by growth stage interaction, 1,000 seed weight tended to increase with increasing growth stages for all environments. The 2017 Langdon environment tended to have the lowest 1,000 seed weight compared to the other environments, and environments in the 2018 season tended to have higher 1,000 seed weights across growth stages. As far as the growth stage by levels of stem cut-off interaction, 1,000 seed weight did not increase significantly during the V4-5. However, 1,000 seed weight did increase at 25% stem cut-off during bolting, at 50 and 75% stem cut-off during 50% flower, and at 90% stem cut-off

during 90% flower (Table 4.5). A possible explanation for this interaction could be that plant

treated at V4-5 growth stage had enough time in the season to recover; however, during the

bolting growth stage seed weight probably increased at 25% stem cut-off due to untreated plants

producing heavier seed. It is assumed the reason for the observed increase in seed weight during

the 50% flower growth stage was due to untreated plants producing heavier seed, but the reason

that 90% stem cut-off had the heaviest seed during 90% flower is probably due to plants with

lower seed yield plant^{-1} producing heavier seed with the remaining seed.

Table 4.5. Mean 1,000 seed weight (g) at four growth stages and five levels of stem cut-off averaged across three replications and five North Dakota environments during 2017 and 2018.

Stem cut-off	Growth stages			
	V4-5	Bolting	50% flower	90% flower
%			g/1,000 seeds	
0	3.62	3.66	3.67	3.70
25	3.57	3.70	3.67	3.74
50	3.67	3.66	3.71	3.84
75	3.65	3.66	3.73	3.84
90	3.61	3.52	3.53	4.06
Means	3.63	3.64	3.66	3.87
LSD (0.05)†			0.13	
LSD (0.05)‡			0.16	

†LSD value for comparing means over levels of stem cut-off with different growth stages.
‡LSD value for comparing means with different growth stages and levels of stem cut-off.

4.4.3. Protein content in seed

ANOVA using PROC GLM indicated a significant main effect for growth stage and

levels of stem cut off (Table 4.2). However, ANOVA did indicate a significant effect for growth

stage by levels of stem cut-off interaction ($P<0.05$) (Table 4.2).

Protein content in seed increased at 50% stem cut-off at V4-5 and bolting growth stages,

at no levels of stem cut-off at 50% flower, and at 90% stem cut-off at 90% flower (Table 4.6). It

is assumed that the reason that these observed increases in protein content were due primarily to

plant stress and regrowth from stem cut-off. The reason being that protein content of seed is primarily the result of rubisco in the leaf tissue being reused in the seed after leaf senescence.

Table 4.6. Seed protein content of seed at four growth stages and five levels of stem cut-off averaged across three replications and five North Dakota environments during 2017 and 2018.

Stem cut-off	Growth stage			
	V4-5	Bolting	50% flower	90% flower
%	% of seed protein			
0	25.6	25.8	26.0	26.1
25	25.3	25.1	26.0	25.8
50	26.2	26.4	25.7	25.5
75	25.8	25.9	26.1	25.7
90	26.1	25.3	26.1	26.8
LSD (0.05)‡	0.8			

‡LSD value for comparing means with different growth stages and levels of stem cut-off.

4.4.4. Oil content in seed

ANOVA using PROC GLM indicated significant main effect for levels of stem cut-off ($P<0.05$) (Table 4.2). However, ANOVA also initiated a non-significant main effect for growth stages and interaction on seed oil content.

As the levels of stem cut-off increased the oil content is decreased. For example, the oil contents were decreased by 0.8, 0.7, 0.7, and 1.5% at stem cut-off levels of 25, 50, 75, and 90%, respectively (Table 4.7). Generally, 90% stem cut-off resulted in the lowest mean oil content. At the higher levels of stem cut-off, the treated plants constitute a greater proportion of the plant population compared to the untreated plants. As a result, there is more competition for resources between plants resulting in less resources available to the individual plant basis to increase oil content. A similar trend was reported by Conley et al. (2008) in a stem cut-off study conducted on soybeans. In that study, at 80% main-stem node removal the oil content was reduced by 4.4 and 8.1% at V2 and V6 growth stages, respectively. These results were similar to the results

found in this study. In both studies, oil content decreased at the increased levels of intensity and growth stages.

Table 4.7. Seed oil content of seed at four growth stages and five levels of stem cut-off averaged across three replications and five North Dakota environments during 2017 and 2018.

Stem cut-off	Growth stage				Means
	V4-5	Bolting	50% flower	90% flower	
%	% of seed oil				
0	41.3	41.1	40.9	41.0	41.1
25	41.7	41.8	40.8	41.1	41.4
50	41.0	40.7	40.9	40.6	40.8
75	40.7	41.0	40.5	40.8	40.8
90	40.7	41.3	40.3	39.5	40.5
LSD (0.05)†			0.5		

‡LSD value for comparing means over growth stages which have different levels of stem cut-off.

4.4.5. Primary branches plant^{-1}

ANOVA indicated a significant main effect for growth stage (P<0.05), levels of stem cut-off (*P*<0.01), environment by level of stem cut-off interaction (*P*<0.05), and the growth stage by stem cut-off interaction (*P*<0.01) on primary branches (Table 4.8). Generally, it was observed that the number of primary branches decreased with increasing levels of stem cut-off and decreasing growth stages.

In respect to plant growth stages, the number of primary branches decreased with increased growth stages. When averaged across all levels of stem cut-off, the growth stages of V4-5, bolting, 50% flower, and 90% flower resulted in a change of -5, -20, -15, and -10% of primary branches, respectively (Table 4.8). A possible explanation for this trend is due to the fact that plants treated at later growth stages have already carried more primary branches. As a result, when treatments were administered the branches below the cut would remain as viable primary

branches. The plants treated at earlier growth stages did not have the branches developed below the cut-off point.

Primary branches plant[-1] decreased as the level of stem cut-off increased. For instance, at 25, 50, 75, and 90% stem cut-off resulted in a decrease of 4, 14, 19, and 24% primary branches, respectively (Table 4.9). It is assumed that due to stem cutting at half of the height of plants resulted in the loss of primary branches. As a result, compensation for the loss of primary branches may primarily be reliant on the increase in secondary branches.

Table 4.8. Sources of variation (SOV), degrees of freedom (df), and mean squares for evaluated traits combined across four environments (Env) during 2017 and 2018.

		Plant height	Prim. branches plant[-1]	Sec. branches plant[-1]	Biomass plant[-1]	Seed yield plant[-1]	Pods plant[-1]	Seeds pod[-1]	Harvest index plant[-1]
SOV	df	MS	MS	MS	MS	MS	MS	MS	MS
Env.	3	2322.6	11.9	2.4	301.0	173.2	4791.0	63.4	95.3
Rep(Env)	4	57.9	0.5	0.3	15.8	1.7	919.7	1.5	14.1
Growth stage (G)	3	119	2.7*	1.3	89.4*	27.8**	10313.7**	2.3	293.7**
Env x G	9	100.9	0.7	0.9	15.9	1.8	923.9	5.7*	33.7**
Stem Cut-off (C)	4	531.2	5.4**	4.4	111.9	30.5	10511.9*	2.9	203.5**
Env x C	12	1204.0**	0.9*	3.9**	151.4**	15.4**	3203.5**	9.4	21.8*
G x C	12	43.9	1.0**	2.9**	44.7	6.2	1923.4	4.7*	55.7**
Env x G x C	36	50.1	0.3	1.0	33.3	4.1	1090.1	2.1	10.1
Error	76	51.3	0.4	1.1	25.4	3.4	843.2	2.8	11.5
Total	159								
CV%		6.5	18.5	29.6	26.4	27.2	27.4	10.4	11.7

* and ** indicates a significance at an alpha of 0.05 and 0.01, respectively.

In regards to the environment by level of stem cut-off interaction, primary branches plant[-1] decreased as level of stem cut-off increased for all environments. The environment with the lowest number of primary branches plant[-1] was Carrington in 2018. It is possible that above normal rainfall and higher temperatures early in the season could have influence plants ability to compensate from stem cut-off damage.

As for the growth stage by level of stem cut-off interaction, primary branches plant[-1] decreased significantly at 50 and 90% stem cut-off during the V4-5, at 50, 75, and 90% stem cut-off during bolting, 75 and 90% stem cut-off during 50% flower, and at 75 and 90% stem cut-off during 90% flower (Table 4.9). A possible explanation could be that at the treated plants represent a larger proportion of the population as level of stem cut-off increased, and plants were less able to compensate as growth stages increased..

Table 4.9. Primary branches plant[-1] at four growth stages and five levels of stem cut-off averaged across two replications and four North Dakota environments during 2017 and 2018.

| Stem cut-off | Growth stages | | | | Means |
	V4-5	Bolting	50% flower	90% flower	
%	Primary branches plant[-1]				
0	4.0	4.0	4.0	4.0	4.0
25	4.2	4.0	3.6	3.7	3.9
50	3.6	3.2	3.6	3.4	3.5
75	3.9	2.9	2.9	3.3	3.3
90	3.6	2.0	3.0	3.5	3.0
Means	3.9	3.2	3.4	3.6	
LSD (0.05)‡	0.5				
LSD (0.05)†	0.4				
LSD (0.05)‡	0.6				

‡LSD value for comparing means over growth stages which have different levels of stem cut-off.
†LSD value for comparing means over levels of stem cut-off with different growth stages.
‡LSD value for comparing means with different growth stages and levels of stem cut-off.

4.4.6. Secondary branches plant[-1]

The ANOVA indicated a significant interaction between the environment by level of stem cut-off interaction ($P<0.01$) and the growth stages by stem cut-off interaction ($P<0.01$) on secondary branches (Table 4.8). However, it showed a non-significant main effect for growth stage and level of stem cut-off on number of secondary branches.

In regards to the environment by level of stem cut-off interaction, secondary branches plant^{-1} increased as level of stem cut-off increased. However, the Carrington 2018 environment tended to produce few secondary branches plant^{-1} compared to the other environments.

As for the growth stage by level of stem cut-off interaction, secondary branches plant^{-1} decreased as growth stage increased and increased as level of stem cut-off increased. Secondary branches plant^{-1} increased at 75% stem cut-off during bolting, at 50 and 90% stem cut-off during 50% flower, and at 75 and 90% stem cut-off during 90% flower (Table 4.10). There was no significant increase in secondary branches plant^{-1} at the V4-5 growth stage. A possible explanation for these increases observed could be that the proportion of treated plants at higher levels of stem cut-off represent a higher proportion of the population. Since treated plants would produce more secondary branches plant^{-1}, the overall secondary branches plant^{-1} would increase.

Table 4.10. Secondary branches plant^{-1} at four growth stages and five levels of stem cut-off averaged across two replication and four North Dakota environments during 2017 and 2018.

Stem cut-off	Growth stages			
	V4-5	Bolting	50% flower	90% flower
%	Secondary branches plant^{-1}			
0	3.3	3.3	3.3	3.3
25	3.3	3.6	2.7	2.8
50	3.0	3.8	3.8	2.5
75	3.9	4.8	3.2	3.5
90	3.8	3.3	3.7	5.0
Means	3.5	3.8	3.3	3.2
LSD (0.05)‡	1.0			

‡LSD value for comparing means with different growth stages and levels of stem cut-off.

4.4.7. Biomass plant^{-1}

ANOVA indicated a non-significant main effect for the growth stages, and growth stages by stem cut-off interaction on mean plant biomass. On the other hand, the ANOVA did indicate a significant main effect for growth stage *(P<0.05)* and environment by level of stem cut-off

interaction ($P<0.01$) on mean plant biomass (Table 4.8). Generally, plants treated at increasing levels of stem cut-off and growth stages experienced a decrease in plant biomass.

In this study, we have identified that an increase in growth stage resulted in a reduction in plant biomass. For example, at V4-5, bolting, 50% flower, and 90% flower resulted in a reduction of plant biomass of -1.9, 6.3, 13.0, and 13.5%, respectively (Table 4.11). It is thought that as maturity of treatment increased, remaining plants had a decreased ability to compensate for stand reduction. Even though surviving plants would have a greater availability of resources, there was not enough time in the season for the plants to take advantage of these resources and produce new growth.

Biomass plant[-1] decreased as level of stem cut-off increased across all environments. The 2018 Prosper environment observed a decreased as level of stem cut-off increased. However, the biomass plant[-1] tended be greater at this environment compared to the other environments. It is possible that higher soil moisture availability and soil fertility could have resulted in possibly higher biomass plant[-1] compared to the other locations.

Table 4.11. Biomass plant[-1] at four growth stages and five levels of stem cut-off averaged across two replications and four North Dakota environments during 2017 and 2018.

	Growth stages			
Stem cut-off	V4-5	Bolting	50% flower	90% flower
%	Plant biomass (g)			
0	20.7	20.7	20.7	20.7
25	24.3	22.6	17.7	19.0
50	18.6	20.6	20.8	17.1
75	21.9	20.6	14.9	15.7
90	19.9	12.7	15.8	17.1
Means	21.1	19.4	18.0	17.9
LSD (0.05)†		2.0		

†LSD value for comparing means over levels of stem cut-off with different growth stages.

4.4.8. Yield component: seed yield plant[-1]

ANOVA indicated a non-significant main effect for the growth stages, and the growth stages by stem cut-off interaction on mean plant seed yield (Table 4.8). On the other hand, It did indicate a significant main effect for growth stage ($P<0.01$) and interaction between environment and level of stem cut-off ($P<0.01$) on seed yield plant[-1].

The general trend was that increased growth stages resulted in a decrease in seed yield plant[-1]. For instance, when averaged across all levels of stem cut-off , growth stages at V4-5, bolting, 50% flower, and 90% flower resulted in a decrease in seed yield plant[-1] of -4.5, 7.6, 18.2, and 24.2 %, respectively (Table 4.12). It is assumed that as growth stages increases, the treated plants will have a diminishing capacity to compensate for stem cut-off damage resulting in less seed yield plant[-1].

Seed yield plant[-1] decreased as levels of stem cut-off increased across all environments. The 2017 environments tended to yield less compared to the 2018 environments. A possible explanation for this could be the more arid conditions experienced during the 2017 season resulting in seed yield plant[-1] being typically lower compared to the higher rainfall conditions in the 2018 environments.

Table 4.12. Seed yield plant[-1] at four growth stages and five levels of stem cut-off averaged across two replications and four North Dakota environments during 2017 and 2018.

Stem cut-off	Growth stage			
	V4-5	Bolting	50% flower	90% flower
%	g plant[-1]			
0	6.6	6.6	6.6	6.6
25	8.1	7.3	5.5	6.0
50	5.9	6.7	6.2	5.1
75	7.3	6.4	4.4	3.7
90	6.5	3.6	4.3	3.5
Means	6.9	6.1	5.4	5.0
LSD (0.05)†	0.7			

†LSD value for comparing means over levels of stem cut-off with different growth stages.

4.4.9. Yield component: pods plant^{-1}

ANOVA indicated a significant main effect for growth stage ($P<0.01$) and levels of stem cut-off ($P<0.05$) on pods plant^{-1} (Table 4.8). As a general trend, pods per plant decreased as the growth stage and levels of stem cut-off increased.

In the advance of plant growth stages, a trend of reduction of pods per plant was observed. In this study, at V4-5, bolting, 50% flower, and 90% flower growth stages the number of pods per plant were decreased by 0, 14, 23, and 30%, respectively (Table 4.13). We anticipated that as the plants are advance to maturity, the ability of treated plants to recover from stem cut-off damage is decreased due to limited time in the season. As a result, treated plants may produce less pods per plant as maturity increases.

Table 4.13. Pods plant^{-1} at four growth stages and five levels of stem cut-off averaged across two replications and four North Dakota environments during 2017 and 2018

Stem cut-off	Growth stages				Means
	V4-5	Bolting	50% flower	90% flower	
%	Pods per plant				
0	128	128	128	128	128
25	144	133	100	100	119
50	113	112	117	87	107
75	130	109	75	63	94
90	119	66	79	69	83
Means	127	110	100	89	
LSD (0.05)‡			30.8		
LSD (0.05)†			15.4		

‡LSD value for comparing means over growth stages which have different levels of stem cut-off.

†LSD value for comparing means over levels of stem cut-off with different growth stages.

When the levels of stem cut-off on pods per plant was examined, a similar trend such as an increased levels of stem cut-off resulted a reduced pods per plant was observed. For example, the 25, 50, 50, 75, and 90% stem cut-off resulted a reduction of 7, 17, 26, and 35% pods per plant, respectively (Table 4.13). We have observed that the higher levels of stem cut-off resulted

less primary and secondary branches which may have ultimately reduced the total number of pods plant^{-1}.

In respect to the environment by level of stem cut-off interaction, pods plant^{-1} decreased as level of stem cut-off increased. However, pods plant^{-1} tended to be higher at 2018 Prosper environment compared to the other three environments. It is thought that this was the result of the greater availability of soil moisture and favorable environmental conditions during the 2018 season at Prosper.

4.4.10. Yield component: seeds pod^{-1}

ANOVA indicated a non-significant main effect for growth stage and levels of stem cut-off. However, ANOVA did indicated a significant effect for the growth stage by stem cut-off interaction ($P<0.05$) and the environment by levels of stem cut-off interaction ($P<0.05$) on seeds pod^{-1} (Table 4.8).

A significant increase in seeds pod^{-1} were observed at 50 and 75% during bolting, and at 25 and 50% stem cut-off during the 90% flower growth stage (Table 4.14). The reason for these observed increased in seeds pod^{-1} was not clear. The lowest seeds pod^{-1} was observed at 90% stem cut-off during the 90% flowering growth stage.

In regards to the environment by level of stem cut-off interaction, seeds pod^{-1} increased as level of stem cut-off increased. However, the 2017 Prosper environment experienced an inverse relationship were seeds pod^{-1} decreased as level of stem cut-off increased. It is possible that these results were influenced by the environmental conditions during the 2017 season due to lower soil moisture resulting in a less favorable environment for plant recovery from stem cut-off damage.

Table 4.14. Seeds pod^{-1} at four growth stages and five levels of stem cut-off averaged across two replications and four North Dakota environments during 2017 and 2018.

Stem cut-off	Growth stages			
	V4-5	Bolting	50% flower	90% flower
%			seeds pod^{-1}	
0	13.9	13.9	13.9	13.9
25	14.9	14.9	14.5	15.6
50	13.9	15.8	13.7	14.7
75	15.4	15.5	15.1	13.3
90	15.0	14.6	14.1	12.3
LSD (0.05)‡			1.5	

‡LSD value for comparing means with different growth stages and levels of stem cut-off.

4.4.11. Harvest index plant^{-1}

ANOVA indicated a significant main effect for the growth stage ($P<0.01$), environment by growth stage interaction ($P<0.01$), levels of stem cut-off ($P<0.01$), environment by level of stem cut-off interaction ($P<0.05$), and the growth stage by stem cut-off interaction ($P<0.01$) on harvest index (Table 4.8).

In regards to the effect of growth stages on harvest index, it was observed that at the advanced growth stages the harvest index were decreased. For example, when averaged across all levels of stem cut-off, at V4-5, bolting, 50% flower, and 90% flower growth stages the harvest indexes were reduced by 0, 7, 10, and 20%, respectively (Table 4.15). It is assumed that the treated plants at later plant growth stages had less time to compensate to produce more seed. As a result, the plant produces more biomass will have less seeds plant^{-1} which finally reduces the harvest index.

Harvest index plant^{-1} decreased as growth stages increased. However, it was observed that harvest index plant^{-1} were lower in the 2017 environments compared to the 2018 environments. It is possible that higher rates of flower abortion combined with the decreased

availability of soil moisture could have resulted in lower seed yield plant^{-1} relative to biomass plant^{-1} resulting in a small harvest index plant^{-1}.

In the case of the levels of stem cut-off on harvest index, it was observed that the increased stem cut-off resulted in a reduction of harvest index. For instance, the 25, 50, 75, and 90% stem cut-off resulted in a reduction of harvest index of 3, 9, 14, and 20%, respectively (Table 4.15). Probably, the higher levels of stem cut-off resulted in greater proportion of the plants in plot being treated. Since, these treated plants tend to have low seed yield plant^{-1} compared to their biomass plant^{-1}, would have a lower proportion of seed compared to total biomass resulted in a lower harvest index plant^{-1}.

As for the environment by level of stem cut-off interaction, harvest index plant^{-1} decreased as level of stem cut-off increased. Generally, the 2017 environments had a smaller harvest index plant^{-1} compared to the 2018 environments.

In regard to the growth stage by stem cut-off interaction, no significant decreases in harvest index plant^{-1} were observed when plants were treated during the V4-5 growth stages. A possible explanation for this observation might be because when plants were treated during the V4-5, they were able to recover and experience every little yield loss. However, harvest index plant^{-1} decreased at 90% stem cut-off during V4-5, 50, 75, and 90% stem cut-off during bolting, 50% flower, and 90% flower growth stages (Table 4.15). It is thought that as growth stage and level of stem cut-off increased that plants could not compensate for the damage.

Table 4.15. Harvest index plant^{-1} at four growth stages and five levels of stem cut-off averaged across two replications and four North Dakota environments during 2017 and 2018.

Stem cut-off	Growth stages				Means
	V4-5	Bolting	50% flower	90% flower	
%	Harvest index plant^{-1}				
0	31.9	31.9	31.9	31.9	31.9
25	32.1	31.8	29.9	29.7	30.9
50	30.9	30.2	28.2	26.9	29.1
75	32.9	29.2	27.9	19.7	27.4
90	31.9	25.6	26.4	18.9	25.7
Means	31.9	29.7	28.9	25.4	
LSD (0.05)‡	2.5				
LSD (0.05)†	2.9				
LSD (0.05)‡	3.2				

‡LSD value for comparing means over growth stages which have different levels of stand reduction.
†LSD value for comparing means over stand reduction with different growth stages.
‡LSD value for comparing means with different growth stages and levels of stand reduction.

4.5. Summary

Hail damage can be characterized by several types of plant injuries which are influenced by many factors such as hail size, velocity, destiny etc. In this study, a simulated hail damage on canola was evaluated at four plant growth stages using five levels of stem cut-off damage.

The field experiment was conducted in six different environments in North Dakota during 2017 and 2018. In 2018, one location was abandoned due to severe infection of clubroot disease. It was observed that at advanced growth stages and increased levels of stem cut-off, the seed yield reduced. 90% flower was the most sensitive for stem cut-off resulting in the greatest yield losses. For example, at growth stages, V4-5, bolting, 50% flower, and 90% flower yield losses were 6, 3, 5, and 22%, respectively. This indicated that the 90% flower is the critical growth stage where the stem cut-off impacted the most yield loss. In regards to levels of stem cut-off, the higher stem cut-off resulted in a higher seed yield reduction. The seed yields were reduced by 7, 10, 13, and 16% across the levels of stem cut-off of 25, 50, 75, and 90%, respectively.

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Economic losses resulted from seed yield reduction increased as both growth stage and level of level of stem cut-off increased. However, a regression equation could only be developed for 50% flower and 90% flower. The economic losses per hectare when averaged across all growth stages equated to $52, $104, $156, and $187.50 for stem cut-off levels of 25, 50, 75, and 90%, respectively (Table 4.4). When averaged across all levels of stem cut-off, economic losses equated to $68 and $182 when plants were treated at 50% and 90% flower, respectively (Table 4.4). A possible explanation for this trend could be the result of the inability of the plants to compensate for stem cut-off damage at 90% flower due to the limited time and resources in the season to recover.

Yield contributing traits were also studied to evaluate the effect of simulated hail damage through stem cut-off or stem break on canola yield. Twenty individual plant samples were taken from four environments which showed the individual plant response to 25, 50, 75, and 90% stem cut-off performed at the V4-5, bolting, 50% flower, and 90% flower growth stages. The primary branches plant^{-1}, pods plant^{-1}, and harvest index were significantly reduced by both growth stages and levels of stem cut-off treatments. However, plant height, secondary branches plant^{-1}, plant biomass, seed yield plant^{-1}, and seeds pod^{-1} were significantly reduced by the increased levels of stem cut-off.

Data for all yield seed yield components indicated that stem cut-off damage at earlier growths stages was less detrimental to seed yield loss. Stem cut-off damage initiated during the reproductive growth stages resulted in increased seed yield losses. As growth stage increased, pods plant^{-1} decreased demonstrating the yield compensation was limited at increased maturity.

A regression equation was developed to quantify the seed yield loss. This equation will allow the producers and crop insurers to more accurately assess the impact of hail damage on seed yields with regards to stem cut-off.

4.6. References

Conley, S.P., L. Abendroth, R. Elmore, E.P. Christmas, and M. Zarnstorff. 2008. Soybean seed yield and composition response to stand reduction at vegetative and reproductive stages. Agron. J. 100: 1666-1669.

Fehr, W. R., C. E. Caviness, and J. J. Vorst. 1977. Response of indeterminate and determinate soybean cultivars to defoliation and half-plant cut-off 1. Crop Sci. 17: 913-917.

Fehr, W. R., D. R. Hicks, S. E. Hawkins, J. H. Ford, and W.W. Nelson. 1983. Soybean recovery from plant cutoff, breakover, and defoliation 1. Agron. J. 75: 512-515.

Harper, F.R., and B. Berkenkamp. 1975. Revised growth-stage key for *Brassica campestris* and *B. napus*. Can. J. Pl. Sci. 55:657-658.

Miller, D. G., and F. J. Muehlbauer. 1984. Stem Excision as a Means of Simulating Hail Injury on 'Alaska'Peas 1. Agron. J. 76: 1003-1005.

Miller, J.R. Jr., and M.J. Fuhs. 1987. Results of hail suppression efforts in North Dakota as shown by crop hail insurance data. J. Wea. Mod. 19: 45-49.

National Crop Insurance Services. 2018. 2017 US Crop-Hail Experience. Today Crop Insurance 51:22-23.

National Agricultural Statistics Services (NASS), USDA. 2018. [Online]. Available on https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NORTH %20DAKOTA (verified 1 Feb. 2019)

North Dakota Agricultural Weather Network (NASS), NDSU. Monthly weather data. [Online]. Available on https://ndawn.ndsu.nodak.edu/weather-data-monthly.html. (verified 1 Nov. 2018)

North Dakota Annual Bulletin, NASS. 2018. Canola acreage, yield, production, price, and value North Dakota: 2008-2017. [Online]. Available on https://www.nass.usda.gov/Statistics_by_State/North_Dakota/Publications/Annual_Statistical_Bulletin/2018/ND-Annual-Bulletin18.pdf. (verified 1 Jan. 2019)

Raymer, P.L. 2002. Canola: An emerging oilseed crop. ASHS Press: 122–126.

Soil Survey Staff, NRCS, USDA. Web soil survey. [Online]. Available at https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm (verified 1 Nov. 2018).

Soine, O.C. 1970. Effect of simulated hail damage on flax. Agricultural Experiment Station, University of Minnesota, Miscellaneous Report 92.

Tabachnick B.G. and L.S. Fidell. 2001. using multivariate statisitcs. 4th ed. Harper Collins, New York City, NY.

5. CONCLUSIONS

Hail damage can be manifested in various types of plant damage which are influenced by numerous factors such as hail stone size, velocity, density, and duration. In this study, stand reduction and stem cut-off treatments were examined in canola to determine the loss of seed yield and other yield contributing traits. The two field experiments were conducted in six different environments in North Dakota. However, one environment was abandoned due to an infection of clubroot (*Plasmodiophora brassicae*) disease.

In the stand reduction experiment, four regression equations were developed for each growth stage across all levels of stand reduction. Under the regression equation, the estimated economic loss of canola production per hectare due to stand reduction at V4-5, bolting, 50% flower, and 90% flower growth stages are $207, $258, $292, and $355, respectively, considering the marketing year average price of canola (≈$0.39 kg^{-1} seeds) in 2017.

In the the stem cut-off experiment, regression equations could only be developed for the last two. 50% flower and 90% flower, growth stages. The potential yield losses per hectare in canola due to stem cut-off are $68 and $182 at 50% flower and 90% flower stages, respectively.

Considering the effect of growths stages, the greatest seed yield losses were observed at 90% flower stage, which were 46% and 22% loss for stand reduction and stem cut-off treatments, respectively. However, when considering the levels of stand reduction and plant cut-off, the yield losses were 65 and 15% at 90% stand reduction and plant cut-off treatments, respectively.

Yield components responded differently depending on the types of damage, levels of damage, and growth stages. In the stand reduction experiments, primary branches plant^{-1}, secondary branches plant^{-1}, biomass plant^{-1}, pods plant^{-1}, seed yield plant^{-1}, and harvest index

increased as levels of stand reduction increased. In contrast, these traits were decreased with the levels of stem cut-off increased. The most economic losses were observed for stand reduction for various growth stages as well as different levels of stand reduction compared to stem cut-off.