Growing Season Weather Impacts on Canola Phenological Development and Quality

By

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ABSTRACT

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This project investigated the phenological development of canola through the 2009 growing season in the western Canadian prairies and quantified the effects of 624 weather parameters on nine canola quality parameters from 247 samples of Canada No. 1 canola. Predictive models were created to utilize as few of the most strongly correlated weather predictors as possible to explain a maximum amount of variation in each of the quality parameters.

An intensive field study carried out at seven sites across Manitoba measured weather conditions and followed canola crop development from seeding through swathing, harvest or physiological maturity. These data were used to produce an index with six Physiological Day (P-Day) thresholds corresponding to specific growth stages. A comparison to the thresholds determined from a previous study suggested that current varieties require fewer heat units for early vegetative growth stages, more heat units during reproductive stages, and slightly greater P-Day accumulations to reach maturity.

Canola samples from the field study were combined with western Canadian canola samples from collaborating companies and the 2008 and 2009 Canadian Grain Commission Harvest Surveys for quality analysis. The samples were analysed for oil content, protein content, oleic, linoleic, linolenic, and total saturated fatty acid contents and iodine value. Weather data from the intensive field study, collaborating companies, the Canadian Wheat Board and Environment Canada weather stations nearest each canola sample were compiled and arranged from the seeding to swathing date of each canola sample. These data were then used to calculate the accumulation

of P-Day values from seeding until each of the six phenological growth stages. Partial Least Squares analysis was utilized to produce predictive models for each of the nine quality parameters.

The results indicated that environmental parameters, especially temperature, had a significant impact on canola quality. The predictive models explained between 7 and 49% of the variation in individual quality parameters. The models for saturated fatty acids, glucosinolates and iodine value explained the highest amount of variation and the model for chlorophyll explained the least. Oil content was positively impacted by a longer duration of temperatures below 11-14^{o}C throughout the reproductive stage, while protein was positively impacted by cool temperatures at early flowering and high temperatures throughout pod and seed development. Chlorophyll was strongly impacted by the moisture balance throughout early to mid reproductive stages and glucosinolates content was affected by conditions that impacted nutrient availability.

Total saturated fatty acid content was positively impacted by cool temperatures throughout late vegetative and early reproductive stages. Moderate predictability of the individual fatty acid content models may have been indicative of either successful breeding of current canola varieties with relatively stable quality characteristics across a range of growing conditions or the complex interactions between oil content and the individual fatty acids measured.

Producers looking to maximize canola quality and canola breeders interested in creating varieties more resistant to the specific weather condtions which impact canola quality could benefit from this study. Predictions of crop quality would also be an asset to those marketing Canadian canola as an export.

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TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

1.0 LITERATURE REVIEW

1.1 Introduction

Canola, whose name is derived from the combination of "Canada" and "oil", was developed from rapeseed in the early 1970s (Stefansson and Kondra 1975; CCC 2011b) using traditional plant breeding techniques, and is currently the only 'Made in Canada' crop (CCC 2011b). Rapeseed was originally produced in Canada as an industrial lubricating oil and was largely used during the World Wars for steam engines and machinery. As production increased, its use as an edible vegetable oil was investigated and developed. The first canola cultivar, Tower, made its debut in 1974 as the first low glucosinolates, low erucic acid rapeseed (Stefansson and Kondra 1975), and has since been followed up by numerous canola varieties (CCC 2011b). The domestic use of the oil for salad dressings, margarine and shortenings led to an increase in production and the subsequent expansion into the export market (Craig 1971).

The canola industry has grown at an impressive rate in a short time and has become one of the most profitable crops in western Canada. Based on the three year average of the crop years 2009/10 through 2011/12, the canola sector has provided over 249,000 jobs to Canadians, including 51,500 to canola producers, and annually contributed about $19.3 billion dollars to the Canadian economy (LMC International Ltd. 2013). Increasing canola acreage (up to 21,743,800 acres in 2012) in western Canada has meant that it appears with increasing frequency in crop rotations. More canola is grown now than ever before. In 2012, Canadian canola production was 13,868,500 tonnes

(Statistics Canada 2013), with about 85% of it being exported to countries around the world (CCC 2011a). Innovative breeding techniques in Canada drive the production of high quality, high yielding varieties of canola, some of which are even tailored to customer preferences (e.g. a specific fatty acid profile). Due to the undesirable effects of glucosinolates and erucic acid in the processing of canola oil and for consumption of canola meal, breeding strategies to reduce both these components have continued.

As the crop developed, the definition of canola evolved along with it, progressively reducing the allowable glucosinolates and erucic acid content as time passed. Currently, the specifications for the crop in Canada are "less than 18 μmol of total glucosinolates per gram of whole seed at a moisture content of 8.5%" and "less than 1% of all fatty acids as erucic acid" (Daun and Adolphe 1997). The Canola Council of Canada states that the internationally regulated standard is "seeds of the genus *Brassica* (*Brassica napus*, *Brassica rapa* or *Brassica juncea*) from which the oil shall contain less than 2% erucic acid in its fatty acid profile and the solid component shall contain less than 30 micromoles of any one or any mixture of 3-butenyl glucosinolate, 4-pentenyl glucosinolate, 2-hydroxy-3 butenyl glucosinolate, and 2-hydroxy- 4-pentenyl glucosinolate per gram of air-dry, oil-free solid" (CCC 2011b).

1.2 The Evolution of Canola Quality

1.2.1 Erucic Acid

Even before the modern definition of canola was established, Sims (1964) described the fatty acid profile of a zero-erucic acid rapeseed variety. His results showed that zero erucic acid rapeseed not only successfully eliminated the fatty acid, but also significantly increased the oleic acid content (which filled the void left by a drop in erucic

acid content) and increased linoleic acid content to some degree, in comparison to the high erucic acid varieties. Craig (1961) also found a negative relationship between erucic acid and oleic acid, reporting a correlation coefficient of r = -0.975 between the percentage of the two fatty acids of 6 *Brassica* varieties, and a weak relationship between erucic acid and linoleic acid, while linolenic acid content was unaffected.

Canvin (1965) reported a similar inverse relationship between erucic acid and oleic acid content at varying temperatures. Comparing temperature effects on low erucic acid rapeseed (LEAR) and high erucic acid rapeseed (HEAR), Yaniv et al. (1995) determined that higher temperatures resulted in greater oleic but lower erucic acid content in HEAR, while higher temperatures resulted in only a slightly greater oleic acid content in LEAR which contained nearly zero erucic acid.

Despite accounting for less than 1% of the canola oil content in 1990, erucic acid content continued to decrease in western Canadian canola over subsequent years (Barthet 2009). Shi et al. (2003) credited the decrease in erucic acid content of *Brassica napus* to successful breeding strategies that exploit the significant effect genetics can have on the maternal plant. They also reported genotype by environmental interactions affecting erucic acid, suggesting there is still some room for improvement in the stability of low erucic acid content across environments. The average level of erucic acid content in western Canadian canola has stabilized at 0.01%, where it has remained from 2008 through 2012 (Barthet 2012).

Although most of the industry is moving toward low or zero erucic acid canola varieties, specialized markets for HEAR still exist. Bahrani and McVetty (2008) concluded that there are still ineffeciencies in these breeding programs too, due to the

effectiveness of moderate and high (genetic) selection pressures on erucic acid content as well as oil, protein and glucosinolates content of greenhouse-grown HEAR samples.

1.2.2 Glucosinolates

Another quality parameter which has been dramatically reduced over the last decade is glucosinolates content (Barthet 2009). Downey and Craig (1969) noted that glucosinolates primarily consist of three isothiocyanates which can have detrimental effects on both oil processing and livestock that consume rapeseed high in glucosinolates (Bell et al. 1971). Bell et al. (1971) discovered that diets high in glucosinolates inhibited growth and exhibited a negative relationship with weight gain in mice. In another study, Bell et al. (1972) determined that high glucosinolate rapeseed meal was associated with lower feed intake, lower weight gain, less efficient feed conversion and thyroid enlargement. Consuming of rapseed meal with high glucosinolate levels caused substantial thyroid enlargement, decreased egg production, and decreased Haugh unit values in layer hens, while consuming of rapeseed meal with low glucosinolate had no negative effect on the the liver, spleen, or egg production and only caused a slight enlargement of the thyroid (as opposed to a substantial enlargement) (Thomas et al. 1978). Furthermore, both high and low glucosinolates rapeseed meal reduced the iodine content of milk when fed to dairy cows (at 25% of the grain mix) and increased the weight of liver and thyroids of calves fed diets with rapeseed meal. However, low glucosinolates rapeseed meal did not affect feed intake, weight gain, hemoglobin, or red blood cell count, while diets with high glucosinolates rapeseed meal reported lower values for all these parameters (Papas et al. 1979).

The success of canola breeding programs may be partially due to genetics having a greater effect on glucosinolates content than environment (Pritchard et al. 2000).

However, glucosinolates content is still significantly affected by environmental parameters (Mailer and Pratley 1990; Pritchard et al. 2000; Aksouh et al. 2001), including soil properties and nutrient availability along with weather parameters. Interestingly, Daun (2006) determined a strong positive correlation between yield and glucosinolates content, which he suggested may be due to their mutually beneficial relationship with the soil sulfur (S) content. Sulfur has an important role in determining the glucosinolates content of the seed (Mailer 1989) because glucosinolates are S-containing compounds (CIGI 1993). This nutrient may also affect glucosinolates content indirectly by improving plant health, as it supports normal plant growth through involvement in chlorophyll production (Marschner 1986 –as cited in Grant and Bailey 2003) and oil synthesis (Mailer 1989). All these plant uses for S drive up the need for the nutrient, resulting in a canola requirement which is nearly twice that for cereal crops (MAFRI 2013).

1.2.3 Chlorophyll

The combination of lower erucic acid and lower glucosinolates properties gave canola the potential to become a popular oil for cooking and human consumption. However, the processing required for this product also highlighted the need for oil with low chlorophyll content. Chlorophyll gives oil an undesirable greenish or brownish colour (CIGI 1993) and promotes oxidation, which makes the oil less stable and more reactive, allowing for potential deterioration (Endo et al. 1984; CIGI 1993), and difficulty for hydrogenation (Mag 1983). While chlorophyll can be removed from oil, the process is costly (Hickling 2005).

Ironically, chlorophyll's role as photosensitizer, which allows it to assist photosynthesis in the chloroplasts and maintain plant growth (Taiz and Zeiger 2006) also

makes it difficult to process. This is due to photosensitizers' ability to oxidize oil in the presence of light (Endo et al. 1984).

In order to combat high chlorophyll content, breeding efforts were directed toward reducing it. Fortunately, genotype has been shown to affect chlorophyll content in canola (Ward et al. 1995; Daun 2006). Unfortunately, the shift in production from *Brassica rapa* to *Brassica napus* was accompanied by an increase in background chlorophyll value (Daun 2003) and may be part of the reason for the lack of decrease in chlorophyll values over the past 30 years (DeClercq 2008). Still, chlorophyll values over the past decade (Barthet 2012) have generally remained within an acceptable level (CGC 2013).

Aside from genetics, chlorophyll is significantly affected by environment (Ward et al. 1995) and is highly weather dependent (Daun 2006). Based on western Canadian weather and canola data, Daun (2006) found that the chlorophyll content in many varieties was inversely related to minimum June and September temperatures, maximum August temperatures, and cumulative precipitation in August. Multiple regression analysis revealed that maximum temperatures in July and September and August precipitation also had notable inverse relationships with chlorophyll content. This finding was supported by DeClercq (2008), who reported chlorophyll was higher in cool, wet growing seasons with early frosts, and lower in hot, dry years.

These environmental effects may be due to the production and degradation patterns of chlorophyll. Rakow and McGregor (1975) described chlorophyll content throughout seed development, which accumulated fairly rapidly from 14 to approximately 30 days after flowering (DAF) and then rapidly decreased from 35 to 42 DAF. Along with chlorophyll content, seed moisture and ethylene content also decreased over time

from the onset of seed colour change through full maturity. Only ethylene and chlorophyll contents followed a similar rapid rate of reduction, while moisture content followed a constant rate of reduction (Ward et al. 1995). Ethylene, which is known as a ripening hormone in several plants (Taiz and Zeiger 2006), was measured along with chlorophyll content because it was hypothesized to control the rate of chlorophyll degradation (Ward et al. 1995). However, since ethylene content peaked after chlorophyll had already begun decreasing, it was concluded that ethylene was not the cause of chlorophyll reduction (Ward et al. 1995).

Many years after the Rakow and McGregor (1975) study, the activities and processes that occurred as a result of photosynthesis were measured by Eastmond et al. (1996) and the chlorophyll content found in *Brassica napus* seeds roughly corresponded to the chlorophyll content in Rakow and McGregor (1975). Under ideal maturation conditions, chlorophyll content decreases throughout maturity to very low levels, but under unfavourable conditions it has been shown to remain at high levels (Appelqvist 1971).

1.3 Breeding for Desired Characteristics

As canola began establishing itself as a major crop in the industry, breeding programs continued to evolve. Investigation into heterosis and the development of hybrid varieties began and Sernyk and Stefansson (1982) reported positive results on early studies. They found hybrid plants were equal or better than one or both of their parental lines in terms of agronomic, yield, and quality parameters, justifying the increased cost of hybrid seeds. Furthermore, days to emergence, flowering, and maturity decreased,

lodging occurrence and protein content decreased, while seed yield, seed weight, harvest index and oil content increased (Sernyk and Stefansson 1982).

These improvements were in line with Diepenbrock's (2000) review, which concluded that an understanding of the components of ideal plant structure along with the synchronization of plant activities, including the production of photosynthates, regulated sink capacity for assimilates, and the growth and development of leaves, stems, pods and seeds are key to maximizing canola yield and should be considered by breeders. More recently, Brandt et al. (2007) confirmed canola produced higher oil and seed yields in hybrid cultivars than in open pollinated cultivars, and use of hybrids still produced higher net returns (Smith et al. 2010). The use of genetically modified (GM) herbicide tolerant canola has also been shown to improve canola quality, reducing weed seed contamination, reducing glucosinolate content and slightly increasing unsaturated fatty acid content (Daun 2004).

In a comparison to mustard, canola had lower above ground dry matter, higher harvest index, fewer pods per plant, more seeds per pod and greater thousand seed weight despite the high phenotypic stability of mustard across environments and strong adaptation to stressful environments (Gunasekera et al. 2006a). However, since canola is more responsive to its environment than mustard, it performed worse than mustard in stressful environments, but outperformed mustard in ideal conditions (Gunasekera et al. 2006b).

In addition, canola generally produced higher oil content and lower protein content than mustard varieties, with the greatest improvements over mustard in earlier seeded crops compared to later seeded and in cooler environments (Gunasekera et al. 2006b). However, Si et al. (2003) determined that genotype only accounted for 5-10% of

the variation in protein content, which may be indicative of the lack of emphasis on protein breeding in canola, as compared to breeding for oil content.

The significant effect of genotype on oil content has been determined in many studies (Canvin 1965; Aksouh et al. 2001; Si et al. 2003; Si and Walton 2004; Chen et al. 2005; Aksouh-Harradj et al. 2006; Daun, 2006; May et al. 2010). This may be a testament to successful breeding efforts, despite claims that there is still room for improvements in the *Brassica* breeding programs (Bahrani and McVetty 2008). Daun (2006) found that between 1992 and 2005, oil content in Canadian Grain Commission (CGC) harvest survey canola increased by an average of 0.05% each year. However the correlation between oil content and crop year was not significant, which he attributed to changing environmental conditions (as opposed to a lack of breeding progress). Barthet (2009) also reported a strong positive trend in western Canada's canola oil content from 1990 to 2009, while a very weak positive trend was noted from 2002-2012 (Barthet 2012), although the survey only included Canada No. 1 canola.

Many studies report an inverse relationship between oil and protein contents (Canvin 1965; Pritchard et al. 2000; Aksouh et al. 2001; Si et al. 2003; Chen et al. 2005, Daun 2006; Gunasekera et al. 2006b). However, Si et al. (2003) and McCartney et al. (2004) did not find a significant correlation between oil content of the seed and protein content of the meal. They concluded that among genotypes, it is possible for oil and protein content selection to occur independently, meaning the content of one trait can be altered without affecting the other (Si et al. 2003).

Grami et al. (1977) investigated the heritability of protein and oil contents, and found that the sum of oil and protein had higher estimates of heritability than either quality parameter individually. They determined a strong negative relationship between

the two parameters, and recognized that it was largely due to competition for carbon and nitrogen. Overall, they concluded that since fewer genes played a role in the heritability of the sum of oil and protein contents (than the role of heritability for oil and protein alone), this trait (the sum of oil and protein) could be used by plant breeders, along with the knowledge of the inverse relationship between oil and protein, to produce varieties with greater oil content.

Across 6 *Brassica* varieties (including one *B. napus* and one *B. rapa*), a genotypic effect was determined for saturated fatty acids (palmitic and stearic), oleic, linoleic and erucic acid, but not for linolenic acid (Craig 1961). The lack of effect on linolenic acid may have been due to the variation in erucic acid content amongst varieties which only impacted oleic and linoleic acid content (Craig 1961).

McCartney et al. (2004) found that most of the variation in the total saturated fatty acid content of canola oil was due to the variation in palmitic acid, which was mainly influenced by genotype (while environment was responsible for explaining most of the variation in stearic, arachidic and behenic acid). The difference in effects of genotype on palmitic and stearic acid was attributed to a highly significant positive relationship between stearic and arachidic acid, suggesting a genetic link between the two.

Still, the constant struggle against a short growing season with limited heat units in western Canada remains a concern. This obstacle can be overcome with additional breeding efforts, as Chen et al. (2005) determined in a study where cultivar affected seedling establishment and the number of heat units required for canola to emerge.

More recently, breeding has focused on the new GM canola varieties which offer herbicide tolerance. As for their effect on canola quality, Daun (2004), who analyzed two different datasets, discovered that GM varieties produced equal or greater oil content,

retained a similar inverse relationship between oil and protein, produced no significantly different erucic acid or saturated fatty acid levels, and produced equal or slightly greater unsaturated fatty acid levels, with no significant difference in linolenic acid content. There were significantly lower glucosinolates and chlorophyll contents in GM varieties, although it was suggested that this was due to a lack of additional weed seeds in the samples compared to weedier, non-GM samples (Daun 2004). Another new breeding tool is market assisted selection, which has great potential to further increase oil content in canola (Zhao et al. 2005).

Along with new techniques, new markets can also be responsible for shifting the direction of breeding programs. The progression of canola establishing itself in the market as a healthy, edible oil, with a low saturated fatty acid content, including both omega-3 and omega-6 fatty acids, required various breeding goals. High polyunsaturated fatty acid content promotes the oil for its health benefits, while lower levels of (polyunsaturated) linolenic acid increase suitability for deep-frying. For example, some of the low-linolenic acid varieties that have been created contain only 2-5% linolenic acid (Baux et al. 2008).

1.4 Physiological Effects on Yield and Morphology

Canola is a cool season crop, with epigeous emergence (cotyledons emerge above the ground), a taproot system and an indeterminate growth pattern (Thomas 1995). Its growth and development can be divided into eight growth stages from emergence to maturity. Canola begins as a seedling with two cotyledons, then grows into the two leaf stage, followed by the four leaf stage and the rosette stage (where leaves are set together in arrangement to optimize incoming light absorption). This is followed by the bolting

stage where the main stem emerges above the leafy rosette, then the flowering stage, the ripening stage where pods form and seeds form, and finally the maturation stage, where the plant dries out until the pods shatter and release the canola seeds (Thomas 1995).

Each of these growth stages has unique environmental requirements from soil temperature and light availability, to optimal air temperature and water supply. Thus, ideal weather conditions for one growth stage are not necessarily ideal for another stage. In general, canola flourishes under cooler, wetter conditions up until maturity and moderately warm, dry conditions at maturation (Thomas 1995).

Brassica rapa (Polish canola) was initially a common canola grown in western Canada because of its quick maturing nature, but more recently *Brassica napus* (Argentine canola) has increased in popularity. *B. napus* is self-pollinating, tends to be taller than *B. rapa* and has large seeds and pods that shatter relatively easily. *B. rapa* is self-incompatible (relies on cross-pollination from other plants) and has good shatter resistance (Thomas 1995).

The shift to slower maturing *Brassica napus* varieties emphasized the importance of early seeding dates to accommodate the short growing season in western Canada. Thurling (1974a) found that the length and description of the developmental stages primarily depend on the date of emergence and environmental conditions that affect the crop during growth. In warm, dry climates such as Australia, canola always seems to reach maturity shortly after high temperatures and low soil moisture conditions occur, regardless of the seeding date (although most Australian varieties are bred to have heat stress tolerance).

Thurling (1974a) found that early seeding allowed canola crops to begin accumulating biomass early in the growing season, and prolonged the growth phase from 'seeding to 50% anthesis'. During this stage, a large amount of leaf and shoot material is produced, along with sufficient root material to hold up the larger plants. The leaves carry out photosynthesis and allow photosynthates to accumulate for subsequent use in oil or protein production. Despite having low net assimilation rates, early seeded crops had the highest relative growth rates and produced the greatest total dry weight and seed yields. However, due to the enormous amount of leaf, shoot and pod material, early seeded canola had a low harvest index (Thurling 1974a).

Late seeded crops had the lowest seed yields, possibly due to the shorter 'seeding to 50% anthesis' duration, reaching 50% anthesis later in the growing season when mean daily temperatures and radiation tend to be higher than those for the early seeded crop at the same growth stage, and consequential limited input of plant metabolites during inflorescence (Thurling 1974a). The low number of pod-bearing branches per plant and pods per plant also likely reduced the yield, despite the high number of seeds per pod (Thurling 1974b). Therefore, the early seeding date allowed for a longer growing season, the subsequent synchronization of preferred weather conditions with developmental stages and sufficient time for proper crop development. However, production of excessive above ground mass occurred in early seeded crops, which may be considered an inefficient use of assimilates (Thurling 1974a).

Unfortunately, Thurling (1974a) determined that *Brassica napus* only produced up to 55% of its total dry weight in the post-anthesis period (when seed development occurs), while *B.rapa*, then known as *Brassica campestris* (Thomas 1995) produced approximately 85% of its total dry matter during this stage. In response to this, Thurling

(1974a) suggested new varieties of *B.napus* should increase the rate of pre-anthesis growth, in order to produce greater seed yields. The prolonged post-anthesis and condensed pre-anthesis duration of current varieties in comparison with previous ones supports this. The shortened pre-anthesis duration allows for sufficient time for seed development including oil production and chlorophyll degradation in the post-anthesis period, while limiting production of unnecessary plant material in the pre-anthesis stages.

In addition to seeding date, genotype also has been determined to influence pre-anthesis and post-anthesis duration in low precipitation sites. Early maturing crops flower during cool, wet conditions, thereby avoiding hotter, drier weather late in the season (Si and Walton 2004). In support of this, Si and Walton (2004) found that longer post-anthesis durations significantly influenced oil content, increasing oil concentration by 1.2% for every additional 10 days of post-anthesis period. Similarly, McGregor (1981) reported that late seeded crops had a reduction in potential seed yield as a result of a lower number of buds, flowers and pods than early seeded crops. He also suggested that the disparity between the greater number of seed abortions in early seeded crops (as opposed to fewer seed abortions in the late seeded crops) was a coping mechanism in the plant to offset a decrease in potential yield caused by late seeding. In another scenario, this coping mechanism (of reducing abortion rates and maintaining higher yield potential) could allow the crop to recover (to some degree) from undesirable weather conditions, such as hail, by reducing their abortion rates and maintaining higher yield potential (McGregor 1981).

Compared to other *Brassica* species, *B. napus* canola was determined to be the last to start flowering, to flower for the shortest duration, and to be the last to reach maturity. However, *B. napus* also had the greatest percentage of emergence, greatest plant survival

rate, greatest yields and the lowest variability in plant stand and for the start of flowering, across environments (Gan et al. 2007).

1.5 Fatty Acid Synthesis

The creation of canola required an alteration of the rapeseed fatty acid profile. Stefansson and Storgaard (1969) investigated the correlations between the substantial individual fatty acids in canola and found that in terms of percentage of total fatty acids, total oil content had a moderately negative relationship with both linoleic and linolenic acid. Conversely, total oil content had a strong positive correlation with oleic acid (an unsaturated fatty acid) and a moderately positive correlation with palmitic acid (a saturated fatty acid). Oleic acid had strong negative relationships with linoleic, linolenic, and palmitic acid, while both linoleic and linolenic acid and linolenic and palmitic acid displayed positive relationships with each other. These relationships were later supported by McCartney et al. (2004) and described in more detail by Pritchard et al. (2000), who reported a negative relationship between oleic acid and linoleic acid of $r = -0.84$, ($P<0.05$) and between oleic acid and linolenic acid of $r = -0.44$ ($P<0.05$). Currently an average canola fatty acid profile, described as a percentage of total oil content, is made up of approximately 62% oleic acid, 20% linoleic acid, and 10% linolenic acid and saturated fatty acid makes up the approximate 7% remainder (Barthet 2012).

The development of these fatty acids was investigated by Fowler and Downey (1970), who described the sigmoid pattern of oil and dry matter production (Figure 1.1 and 1.2). The total accumulation of individual fatty acid amounts generally followed the pattern of an increase at a minimal rate from 7 to 14 days after pollination (DAP), an increase at a moderate rate from 14 to 21 DAP, an increase at a maximum rate from 21 to

35 DAP, and finally an increase at a moderate rate again from 35 to 42 DAP. Naturally, when viewed as a percentage of total fatty acids, these production patterns appear differently, due to the huge proportion of total fatty acids that belongs to oleic acid.

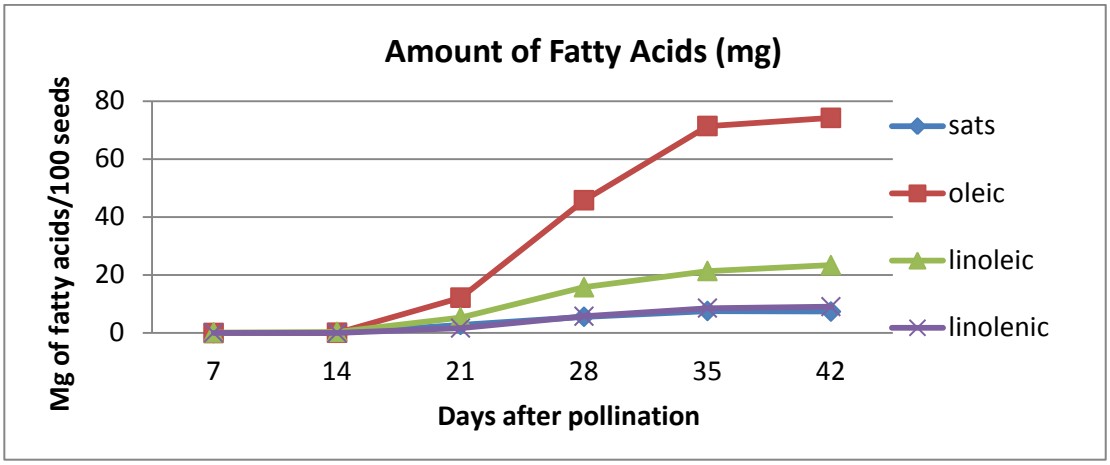

Figure 1.1 Accumulation of major fatty acids in rapeseed, by amount.
(Fowler and Downey 1970)

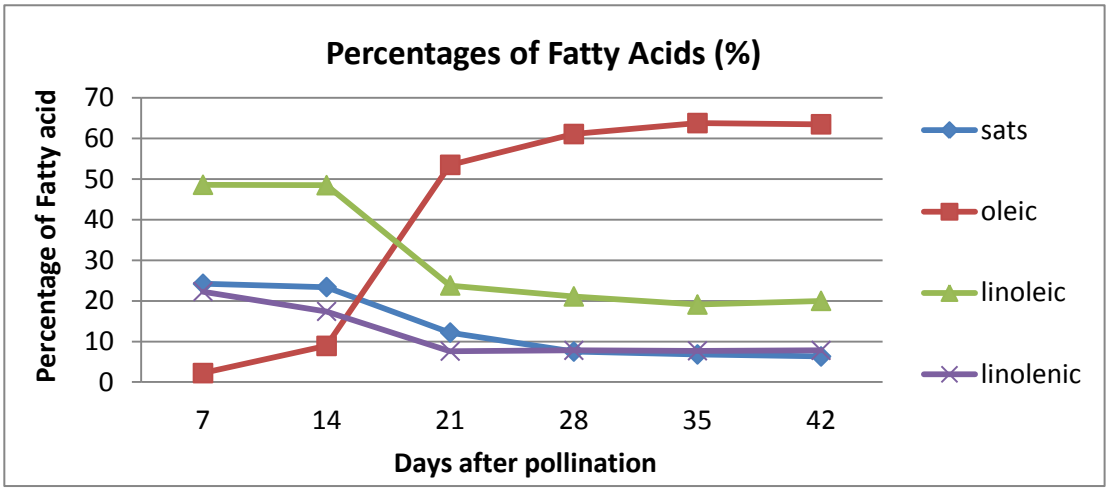

Figure 1.2 Accumulation of major fatty acids in rapeseed, by percentage.
(Fowler and Downey 1970)

Examining the total seed, Rakow and McGregor (1975) followed fresh and dry weight throughout development, thereby describing the pattern of moisture loss throughout the reproductive stages. They found fresh weight of the total plant increased fairly constantly from 14 to 35 DAF, then decreased at a similar rate until the last

measurement was taken at 56 DAF. Dry weight followed a sigmoid curve from 14 to 49 DAF, with a dramatic increase from 21 to 35 DAF, and peaking at 49 DAF.

More recent varieties have slightly shifted the production of unsaturated fatty acid content (mg/g seed) to rapidly increasing from 20 to 30 DAF, followed by a moderate increase until 40 DAF, before slightly decreasing by 50 DAF (Deng and Scarth 1998). In general, however, the pattern of fatty acid accumulation throughout maturity has remained similar to the outline given by Fowler and Downey (1970), and Perry and Harwood (1993).

As more information is collected on fatty acid biosynthesis, a better understanding of the sequence of individual fatty acids accumulation has developed (Barthet 2008; Chen et al. 2011; Harwood and Guschina 2013). The production of fatty acids involves de novo synthesis (via the fatty acid synthase reactions) in the plastid, and after being exported, the Kennedy (glycerol 3-phosphate) pathway in the endoplasmic reticulum (Christie 2013; Harwood and Guschina 2013). These two processes are connected by a pool of actyl-CoA, from which they each draw this intermediate (actyl-Co-A) (Harwood and Guschina 2013). The saturated fatty acids palmitate and stearate, which are created from these processes, are then modified by desaturase or elongation enzymes in the endoplasmic reticulum to produce common canola fatty acids linoleic and linolenic acid (Harwood 2010). Stearate also acts as a precursor to the production of oleic acid, within the plastid (Harwood 2010; Weselake et al. 2010). The simplified desaturation sequence from saturated to common unsaturated fatty acid in canola (the progression from palmitate to stearate to oleic to linoleic to linolenic acid) was given in Stumpf (1972).

The accumulation of fatty acid (triacylglycerol) content over the course of seed development is characterized by a sigmoid curve that has been described in three specific

phases (Perry and Harwood 1993). The first phase is rapid cell division where little lipid synthesis occurs and takes place from fertilization until 18 DAP. The second is the rapid accumulation of storage material (including oil) from 18 to 40 DAP and the final stage is desiccation, which takes place from 40 to 65 DAP or maturity, where minimal storage material is produced and the seed dries out (Perry & Harwood 1993).

A comparison between data from Perry and Harwood (1993) and Rakow and McGregor (1975) suggests varietal improvements in the past may have caused the shift in fresh weight accumulation, from a more moderate increase over 14 to 35 DAP towards a more rapid increase from approximately 17 to 40 DAP, which peaks at a higher value (approximately 5 days later than the 1975 study reported).

Certain current breeding strategies focus on altering the activity of enzymes involved in the Kennedy Pathway, since Chen et al. (2011) found positive correlations (although not always significant) between oil content and the activity of enzymes involved in the Kennedy Pathway over the 18 to 39 DAP duration. Changing the quantity of certain enzymes or precursors of the fatty acid synthase reactions or the Kennedy pathway has already been shown to increase seed weight and oil content in transgenic rapeseed (Weselake et al. 2010; Chen et al. 2011).

1.6 Environmental Effect on Canola

Canola breeding has been successful in many areas, with the popular *B. napus* consistently out-yielding *B. rapa* under cool conditions. However, Johnston et al. (2002) suggested that while canola is well-adapted in terms of water efficiency to the cool, short growing seasons characteristic of western Canada, there is still room for improvement in the crop's ability to handle heat and drought stresses. Furthermore, environment was still

found to have a substantial impact on oil, protein, glucosinolates, oleic, linoleic, linolenic, saturated fatty acids (Pritchard et al. 2000), chlorophyll (Daun 2006) and iodine value (Daun 1981). It has even been determined that environment affects protein more than oil concentration (Sernyk and Stefansson 1982; Gunasekera et al. 2006b).

1.6.1 Temperature Effects on Quality and Yield

Despite all the genetic improvements in canola varieties (increasing genetic potential and robustness) the environment still has an impact on canola quality and resulting yield, with temperature accounting for a substantial portion of the environmental impact (Daun 2006). As seeded canola acreage in Canada has increased (Statistics Canada 2013) so has the range in environments and climatic conditions that canola is being grown under. In addition, recent breeding strategies for improved yield and quality have led to longer reproductive durations, throughout which the crop is more sensitive to the impacts of temperature (Gan et al. 2004).

Average daily temperature (rising from approximately 12 to 18^{o}C) throughout the post-anthesis period has been shown to have a negative relationship with seed yield (falling from approximately 3400 to 500 kg/ha), reducing total yield by 289 kg/ha for every one degree increase in temperature (Si and Walton 2004). These findings are supported by Kutcher et al. (2010), who found that mean and maximum temperatures in Saskatchewan were negatively correlated with canola yields. Similarly, Yaniv et al. (1995) determined that cooler conditions improved yield components, including increased seed weight/pod, 1000 seed weight, number of seeds/pod, length of ripe pod and greater number of days to maturity in both high-erucic acid and low-erucic acid *Brassica* varieties.

The preferred temperature for canola growth and development is between 12^{o}C and 30^{o}C, with an optimum temperature estimated at 21^{o}C (Thomas 1995). Generally, canola grown under the temperatures at the lower end of the preferred temperature range throughout development produces higher oil content (Canvin 1965; Yaniv et al. 1995; Pritchard et al. 2000; Si & Walton 2004; Gunasekera et al. 2006b), lower protein content (Canvin 1965), higher chlorophyll (as a result of delayed maturity and possible early frosts) (DeClercq 2008), lower glucosinolates (Aksouh et al. 2001), and generally higher unsaturated fatty acids (Canvin 1965). However, the details of the temperature duration and intensity that transpire throughout specific growth stages provide a more precise and accurate account of these temperature effects on quality parameters.

Oil content has been shown to significantly increase with lower minimum temperatures, especially throughout June (Daun 2006). Yaniv et al. (1995) also observed that canola grown under low minimum and maximum temperatures (12/17^{o}C versus 17/22^{o}C regimes) produced higher oil content. However, average maximum and highest maximum temperatures during seed development had a more significant effect on oil content ($P<0.001$) than average minimum and lowest minimum temperatures ($P<0.05$) during the same growth stage (Pritchard et al. 2000) with total oil content decreasing by 0.38% per 1.0^{o}C increase in average maximum spring temperature. In addition, average daily temperatures throughout the post-anthesis period had a negative relationship with oil concentration with a decrease of 0.68% for each degree increase in post-anthesis temperature (Si and Walton 2004). However, the strong influence of maximum temperatures may be due to the hot, dry Australian conditions where these experiments were conducted.

Conversely, a positive trend between temperature and protein was reported by Gunasekera et al. (2006b), where protein was positively correlated to average daily temperature ($r^2 = 0.42$) and average daily maximum temperatures ($r^2 = 0.49$). A significantly positive relationship was also determined between average maximum and highest maximum temperatures and seed protein in Pritchard et al. (2000). In a western Canadian study, July maximum temperatures were found to have a significantly positive effect on protein content (Daun 2006).

Their opposing relationships with temperature highlights the inverse relationship between canola oil and protein content (Canvin 1965). It has been found to be very strong in some studies, with correlations of $r = -0.75$ ($P<0.001$) (Pritchard et al. 2000) and $r = -0.73$ (Si et al. 2003). Sometimes this correlation is explained by the increase in oil concentration coming at the cost of seed protein (Si et al. 2003). However, according to Canvin (1965), it is an effect of increased nitrogen availability at higher temperatures allowing for greater nitrogen absorption. He also recognized the potential competition for carbon skeletons that the additional nitrogen may ignite, regarding the plant's production of protein or fat and oil. This may explain why one study found that nitrogen application rates affected oil yield and oil content, with oil yield increasing and oil content decreasing with greater nitrogen rates (Karamzadeh et al. 2010).

Conversely, Si et al. (2003), concluded that the two genetic traits responsible for the expression of protein and oil concentration are not genetically correlated, and therefore could both be increased through breeding, if desired. This theory was supported by Aksouh-Harradj et al. (2006) who found no correlation between oil and protein in their

study although it involved heat stress from extreme temperatures (without any acclimatization), during a vulnerable stage in development.

It has been established that when a species of seed is grown in colder climates it will produce greater unsaturated fatty acid content than one grown in a warmer climates, where higher levels of saturated fatty acids are produced (Hilditciit 1956; Canvin 1965). In particular, higher maximum temperature had a significantly negative ($P<0.001$) impact on linolenic acid content (Baux et al. 2008).

Canvin (1965) attributed the variation in fatty acid profiles to the activity or inactivity of enzymes. He concluded that higher temperatures favoured saturation and thereby the inactivation of enzymes that converted oleic to linoleic or linolenic acid while maintaining production of oleic and saturated fatty acids. This was supported by the high erucic acid variety study by Yaniv et al. (1995) which determined that quantity of erucic acid accumulated after anthesis varied depending on the temperature under which it matured, with low temperatures delaying the start of production but ultimately resulting in a greater quantity. More specifically, plants developing under a cooler temperature regime (12/17^{o}C) produced 8.8% greater erucic acid content than those grown under a warmer regime (22/27^{o}C), along with lower oleic acid and linoleic acid content, and slightly higher linoleic acid content (Yaniv et al. 1995).

Conversely, Baux et al. (2008) suggested that temperature affected the linolenic and oleic acid, but not the linoleic synthesis (in low-linolenic rapeseed). Therefore, under low temperatures oleic acid production would favour desaturation to linoleic acid, and desaturation from linoleic to linolenic acid would also be favoured, resulting in greater linolenic acid, lower oleic acid and an unchanged value of linoleic acid. This was

supported by Deng and Scarth (1998) who determined oleic and linoleic acids had contrasting trends when grown under low, intermediate, or high temperatures. The lowest oleic acid and highest linoleic acid values were found in canola grown at the intermediate temperature, while high oleic acid values and low linoleic acid values occurred at both cool and hot temperature regimes.

Trémolières et al. (1978) added to the knowledge about fatty acid production by examining the incorporation of fatty acids into rapeseed over various growth stages and oleate desaturation activities. They found that temperature had an immediate and long-term effect on fatty acid levels, which was in general agreement with Canvin (1965), and that oxygen concentration and enzyme activity influenced by temperature were the main culprits behind the variation in fatty acids. Trémolières (1982) later suggested that while other factors such as oxygen concentration and temperatures may affect final fatty acid content, the dominant factor is the genetic programming in the enzyme and how it reacts to these external factors that determines how much the final fatty acid content will change.

Furthermore, Trémolières et al. (1978) found that temperature could have a fairly immediate effect, with a 20 hour treatment at 4 weeks into flowering altering the fatty acid profile, most notably by a huge increase in linoleic acid in addition to a drop in saturated fatty acids and linolenic acid, and an increase in oleic acid. The varying lengths that the temperatures regimes were applied to the plants in terms of day length hours had a huge impact on the final fatty acid profiles, especially when applied at different stages in development (Trémolières et al. 1978). Deng and Scarth (1998) also found that the duration of the temperature treatment had a significant effect on linolenic acid in a conventional variety and on the saturated fatty acid content of a low-linolenic acid

variety. However, LEAR varieties appeared to be less responsive to changes in temperature regimes than HEAR varieties, aside from containing higher linoleic acid and lower linolenic acid content (Yaniv et al. 1995).

1.6.1.1 Effect of Cool Temperatures. Since canola is a cool season crop, moderately low temperatures within the range of temperatures for best growth (Thomas 1995) (which frequently occur in western Canada) are not a growth constraint. Naturally, temperatures below the range of temperatures for best growth (Thomas 1995), especially if they are below 5^{o}C, can hinder growth and extremely low growing season temperatures cause frost damage (see Section 1.6.1.3). Moderately low temperatures have generally been shown to have a positive impact on canola yield (Angadi et al. 2000; Aksouh et al. 2001; Gan et al. 2004) and quality (Canvin 1965; Pritchard et al. 2000). However, since they can cause delayed maturity (Daun 2007), low temperatures (especially in areas with short growing seasons, such as Canada) can be a concern in terms of allowing adequate time to complete maturity before harvest.

1.6.1.2 Effect of Heat Stress. Canola is a cool season crop and high temperatures can negatively affect yield, quality and general physiology depending on the intensity, duration and timing of the heat stress. More specifically, *B. juncea* and *B. rapa* have higher optimum temperatures for development than *B. napus*, but *B. rapa* is more sensitive to heat stress, although it has been reported that *B. napus* had the hardest time (out of the three *Brassica* species) recovering from stress during flowering (Angadi et al. 2000). In Saskatchewan, canola yields were negatively correlated with the number of days with temperatures above 30^{o}C, especially in lower precipitation areas (Kutcher et al. 2010).

High temperatures can affect canola yields due to their impact on plant physiology. Morrison (1993) found that heat-stressed canola produced an overall lack of synchronization between the male and female reproductive parts. Female fertility was affected to a greater degree than male fertility, including smaller flowers, shrunken anthers, premature pistil emergence and long gynoecium. As a result, some of the pods were short, plump and did not contain seeds, or were distorted, curled and contained stamens and gynoecium (at the end of the racemes). Both temperature and the interaction between temperature and growth stage had significant effects on main shoot fertility, number of pods per plant, seed yield per plant (by main shoot and by branches), seeds per pod and seed weight on *Brassica* crops (Gan et al. 2004). Angadi et al. (2000) also determined that heat treatments during both the early flower and early pod stages caused a significantly higher number of sterile pods.

They also found that intensity of heat stress (a 35/15^{o}C regime versus a 28/15^{o}C regime) had a greater effect on shoot dry matter, seed yield, harvest index, fertile pods per main stem, seeds per pod and seed weight than timing of the heat stress (early flower versus early pod stage). Intensity of heat was also more effective than duration, in a study by Aksouh et al. (2001) which found that seed yield, number of siliques per plant and seed weight were more significantly affected by short, intense heat (5 days with 4-hour heat treatments of 40^{o}C totaling 15 DD), than a longer duration of progressively higher temperatures (5 days of with progressively higher temperatures that peaked at 40^{o}C and totaled 45 DD), with some varieties more affected than others. Aksouh-Harradj et al. (2006) was in agreement with this, determining that short, extremely high temperature stresses (reaching 38^{o}C for 5 hours from 25-29 DAF) reduced seed weight. However, they also determined that moderately high temperature stress (maxing out at 28^{o}C for 14

hours, from 20-29 DAF) generally decreased seed weight. The amount of time at a specific developmental stage can affect the crop as well. Si and Walton (2004) discovered oil concentration increased by 1.2% for each additional 10 days in post-anthesis duration.

In areas that breed for heat tolerance, such as Australia, extremely high temperatures regularly occur and potentially cause increased protein content, palmitic and stearic (saturated) fatty acids, and oleic acid along with reducing oil content and linolenic acid content (Pritchard et al. 2000). Elevated protein content has often been linked to plant heat stress in other studies (Canvin 1965; Pritchard et al. 2000; Aksouh et al. 2001; Gunasekera et al. 2006b).

The intensity of the heat stress and the timing of application also factor into the impact heat stress has on canola quality. Intense heat for short periods throughout late flowering and seed development stage had a significantly negative effect on oil concentration and a significantly positive impact on protein concentration, saturated fatty acid content and glucosinolates concentration. Less dramatic effects were reported in unsaturated fatty acids, with the intense heat resulting in a negative impact on oleic acid, a neutral impact on linoleic acid and a negative impact on linolenic acid. Meanwhile a heat treatment which progressively rose by 5^{o}C each day has less significant effects on some quality parameters (oil, protein and glucosinolates) and no significant effect on unsaturated or saturated fatty acid content (Aksouh 2001).

In regards to the timing of application, intense heat applied slightly earlier (at early seed development) had a significant impact on oil content, but not on protein, glucosinolates or palmitic acid (which makes up the majority of saturated fatty acids) content (Aksouh-Harradj et al. 2006). Palmitic acid has been shown to be more influenced by genotype than environment, which may explain the lack of a temperature

effect in a study by McCartney et al. (2004). A positive impact on oleic acid, a negative impact on linoleic acid and a negative impact on linolenic acid also resulted from the intense heat applied during the equivalent to early seed development stage (Aksouh-Harradj et al. 2006).

The fatty acid profiles that result from heat treatments have been influenced by enzyme activities, according to Aksouh-Harradj et al. (2006). The study reported that short, extremely high temperature stresses (reaching 38^{o}C for 5 hours from 25-29 DAF) reduced oleic desaturase activity without significantly affecting linoleic desaturase activity and reduced oil content, increased oleic acid content, slightly increased saturated fatty acids, and reduced linoleic acid content with no significant effect on protein, linolenic acid or glucosinolates content. However, they also determined that moderately high temperature stress (14 hours of 28^{o}C per day from 20-29 DAF) generally decreased oleic and linoleic desaturase activity, resulting in increased oil and oleic acid content, decreased linoleic acid and linolenic acid content. It was proposed that the difference between the effects of the moderate and high temperature regimes on canola may be due to the acclimatization period in the moderate regime, which may have allowed the plant to adapt to higher temperatures (Aksouh-Harradj et al. 2006).

1.6.1.3 Effect of Cold Stress. If temperatures drop low enough, they endanger the crop with a risk of frost, either in the spring or fall. The Canola Council of Canada (CCC 2011b) noted that in the spring there is an urgency to seed early enough to allow for adequate heat units to accumulate until maturity. However, they also noted that germination is affected by soil temperature, with temperatures below 8^{o}C increasing the number of days until emergence, and below 3^{o}C reducing germination percentage. The frost tolerance of the plants is also related to developmental stage, the moisture content of

the plant and the duration and intensity of the frost. Frost late in development has also been associated with high chlorophyll values, which degrades the crop quality (Thomas 1995).

1.6.2 Precipitation and Water Use Efficiency

Canola requires a large amount of moisture over the course of the growing season. Moisture is essential for biochemical reactions necessary for growth, nutrient absorption, and to help deal with abiotic stresses (Thomas 1995). Compared to cereal and pulse crops, oilseed crops have low water use efficiency (WUE), due to their high water usage, relatively low grain yield and low harvest index across various water regimes (Angadi et al. 2008). Angadi et al. (2008) showed that *B. napus* outperformed *B. rapa* in grain yield, WUE, biomass production and harvest index when averaged across water regimes. It was interesting that the study was unable to conclude whether *B. juncea* was more drought tolerant than *B. napus* or not. However, according to Gan et al. (2007) *B. juncea* was the *Brassica* species best adapted to the drier areas in the northern plains because of its high drought stress tolerance.

Total growing season precipitation had a positive effect on canola yields in Saskatchewan (Kutcher et al. 2010). This depicts how water availability was critical in the western Canadian Prairies (especially in moisture-limited areas), where crop water use and water stress have been deemed critical influences on wheat quality (Jarvis et al. 2008).

Another study was able to calculate that post-anthesis rainfall increased seed yield by 116 kg ha^{-1} for every 10 mm increase in post-anthesis rainfall (Si and Walton 2004). Although water stress had no significant effect on seed fertility and much less impact on seed yield and related components than temperature, it produced a significant effect (P<

0.01) on total seed yield. This was partially the result of a significant difference in seed yield plant^{-1} on the branches rather than the minor difference between seed yield of the main shoot. The interaction between the water stress and the stage at which the water stress was applied also produced a significant effect ($P< 0.05$) on seed pod^{-1} and seed weight (g 1000^{-1}), with the stress applied at the pod stage having the most detrimental impact, followed by flower and bud stage (Gan et al. 2004).

The duration of the irrigation period had a significantly positive effect on yield with a greater number of pods per plant, seeds per pod, seeds per plant, thousand kernel weights and significantly greater total dry matter in crops with irrigation schedules that lasted longer into the plant developmental stages (Krogman and Hobbs 1975). It has also been determined that in low rainfall sites, canola crops flowered later, lengthening the pre-anthesis duration and shortening the post-anthesis duration (Si and Walton 2004).

The total rainfall throughout seed development had a significantly positive affect ($P<0.05$) on oil content in canola (Pritchard et al. 2000) in Australia. This positive relationship was echoed by Si and Walton (2004) who also determined a positive correlation between seed yield and post-anthesis rainfall. More specifically, oil content increased by 0.7% for each 10 mm increase in rainfall (Si and Walton 2004).

Conversely, Pritchard et al. (2000) found that rainfall during seed development had no significant effect on protein content and Si et al. (2003) found that annual rainfall had no significant effect on protein concentration unless early maturing and mid-season data was pooled (which did have a significant effect). This opposed findings from Gunasekera et al. (2006b), who found a negative correlation between protein and rainfall with $r^2 = 0.69$. More specifically, the protein concentration in the seed was found to increase about 0.11% per 1 mm deficit in rainfall and by 0.63% per 1^{o}C increase in

average daily temperatures. Rainfall throughout seed development has also been determined to have a significant effect on linolenic acid (Pritchard et al. 2000, Baux et al. 2008) and stearic acid, but no significant effect on glucosinolates, palmitic, oleic, or linoleic acid content (Pritchard et al. 2000).

1.6.3 Temperature and Precipitation

In a field study carried out by Pritchard et al. (2000) total oil content was generally higher in canola grown in cooler and wetter areas, with temperature being the most integral factor. Similarly, Gan et al. (2004) determined that temperature had a much greater influence on seed yield (g plant^{-1}) than water stress. However, a controlled environment study found that water stress reduced the oil content of canola under both warm and cool conditions (Triboi-Blondel and Renard 1999).

More specifically, Triboi-Blondel and Renard (1999) found that irrigated canola produced significantly lower protein, significantly greater oil content, seed yield, higher siliques m^{-2}, average silique weight, seeds m^{-2} and average seed weight, but lower seeds per silique values under cool conditions rather than warm, water-stressed canola. There was also significantly higher oleic, linoleic, linolenic acid content in the warm, water-stressed canola than either cool irrigated or cool water-stressed samples. There was no significant difference between the saturated fatty acid contents of different temperature or precipitation regimes, except for warm, irrigated samples making up a lesser stearic acid content than cool, irrigated samples. Pritchard et al. (2000) found slightly different results regarding high oleic acid values, with warmer and wetter conditions during seed development yielding higher content, (as opposed to warm, water-stressed conditions corresponding to greater oleic acid values in Triboi-Blondel and Renard 1999).

It can be difficult to separate the impacts of precipitation from temperature in field studies, but Chen et al. (2005) found that a growing season with cool June and July temperatures combined with a dry July and August resulted in a low yielding canola crop with low oil content at one field site. Meanwhile, a slightly warmer, summer with low precipitation in July and August also resulted in low-yielding canola with low oil content at another field site (Chen et al. 2005), showing little impact of temperature. However, May et al. (2010), found that temperature had a greater impact on the oil content than precipitation and Gan et al. (2004) determined seed yield is much more affected by temperature than by moisture stress, with high temperatures producing low yields. Sterility appeared to be more effected by heat stress than water stress too, with heat treatments during the bolting stage often having the least effect.

1.6.4 Phenological Timing

The magnitude of the impact of temperature on canola is often dependent on the growing stage of the crop. For example, canola crops that are planted late in the season will enter the flowering stage later in the season (when average and maximum temperatures are normally higher) and therefore be more likely to experience higher temperatures during oil production (rather than after production is complete, as preferred) and produce lower total oil contents (Thurling 1974a).

Timing plays a role in many aspects of plant production from emergence until harvest. The timing of emergence is influenced by moisture, temperature and soil structure (which consequentially affect nutrient availability). Biological yield or total biomass is a product of growth over time (growth rate) and the length of time (duration) in each growth stage, which is in turn influenced by the amount of light intercepted, as a proportion of total available light for the specific time in the season. The time at which

flowering begins and ends is driven by the supply and photosynthetic assimilates, and will eventually affect flower, pod and seed number. The transfer of assimilates affects the time at which physical maturity will be reached, and temperatures recorded throughout this process affect the final yield production. In order to maximize seed yield, the efficacy of pod development, seed set and seed filling across branches, the synchronization (timing) of the capacity of the source and the capacity of the sink is the most critical factor (Diepenbrock 2000).

Timing plays a key role in the final seed yield in terms of the length of growth stages and the rate of production, according to Diepenbrock (2000). He also suggested that predictive models which describe phenological development can be instrumental in determining yield-limiting factors and could lead to yield improvements. Furthermore, the proper alignment of sink and source capacities should be considered within breeding selection criteria.

As mentioned earlier, canola is reportedly most vulnerable to heat stress from the late bud development through early seed formation (Trémolières et al. 1978; Morrison 1993; Gan et al. 2004). In fact, heat stress (a 35/15^{o}C regime) imposed at the early flower stage can produce more physiological stress, than heat treatments imposed at any other developmental stage (Angadi et al. 2000). Another study which measured the effect of water and temperature stress on total yield determined the reduction in yield increased when applied later in development. The yield reduction was 15% when the stress was applied at bud formation, 58% when applied during flowering, and 77% when applied during pod development (Gan et al. 2004).

Part of the reason plants stressed at earlier growth stages are not affected by heat treatments as much as those stressed later in development, may be that the plant is more

resilient to stress earlier in development and can rebound from unfavourable conditions when necessary (Gan et al. 2004). Interestingly, the time at which the plant experiences stress is visually apparent. Since canola flowers sequentially from the bottom of the raceme to the top, stress experienced later in the season will affect the flowers near the top of the raceme, while stress experienced earlier in the season will affect the flowers near the bottom of the raceme (Morrison 1993).

Heat stress at a certain time in development also impacts the fatty acid profile. Similar to the effects on yield, heat stress applied during late flowering and early seed development (20 to 29 DAF and 29 to 34 DAF) was reported to have the greatest impact of heat on oil content, which is the reason both Aksouh-Harradj et al. (2006) and Aksouh et al. (2001) conducted heat treatments on plants at this sensitive time in development.

Temperature treatments applied later in development (at 6 weeks instead of 4 weeks after flowering) still had an influence on individual fatty acids, but to a lesser extent (Trémolières et al. 1978). The later developmental stage was found to impact linolenic acid content, in a study by Baux et al. (2008), which revealed that minimum daily temperatures which dipped down to at least 13^{o}C over 41 to 60 DAF strongly impacted linolenic acid content. The sums of average and of maximum temperatures from flowering to 60 DAF also had an impact, but to a lesser extent.

When Deng and Scarth (1998) investigated temperature effects on low-linolenic acid varieties, they found as late as 40 DAF temperature still had a significant effect on the fatty acid profile, with high temperatures resulting in higher saturated fatty acid content, lower linolenic acid content and altering oleic and linoleic acid at low and high (not moderate) temperatures. Interestingly, moderate heat treatments from 0 to 40 DAF

only resulted in increased saturated fatty acid content in low-linolenic varieties grown under higher temperatures, but not in conventional varieties (Deng and Scarth 1998).

Not only does longer exposure to high temperatures have a greater effect on canola, but so do the initial growth conditions. Aside from confirming that late bud to early seed development stage is the most vulnerable to heat stress, Morrison (1993) found that canola initially grown in warm temperatures, and then transferred to the cool temperatures before early flower stage had significantly higher raceme fertility and number of seeds per pod than those transferred after this stage. Alternatively, canola initially grown in cool temperatures had significantly lower raceme fertility and seeds per pod if they were transferred to warm temperatures before late flowering stage rather than after the late flowering stage.

1.6.5 Genotype by Environmental Interaction

Amongst rapeseed cultivars, variety by location had no significant effect on palmitic, oleic, linoleic, linolenic or erucic fatty acids in one study (Craig 1961). On the contrary, location had a significant effect on saturated fatty acids (palmitic and stearic), oleic, linoleic, linolenic and erucic acid content. It was suggested that this locational effect on linolenic acid content was related to moisture conditions as a result of irrigation or soil type, with the highest erucic and linolenic acid values but the lowest oleic and linoleic acid values in the grey wooded soil zone, and the lowest erucic and linolenic acid values but higher oleic and linoleic acid values in Brown and Dark Brown soil zones.

Studies on relatively recent canola varieties also found that genotype by environmental interactions did not play a big role in explaining the variability of total saturated fatty acids, as they were more stable across environments when considered together than as individual saturated fatty acids (McCartney et al. 2004).

Conversely, Si et al. (2003) found that location had a greater effect on oil concentration than genotype, with the effects of location likely due to the interaction of "rainfall, temperature, soil water availability, soil type, and crop ontogeny during seed development".

The genotype by environment interaction is a concern because, compared to mustard, canola has been found to have average or below average phenotypic stability across environments, meaning it is more responsive to environmental changes and less adaptable to diverse environmental conditions (Gunasekera 2006a). This cost to canola comes with the benefit of being able to produce higher seed yields and often higher oil concentration in preferential environments. Alternatively, mustard is better adapted to stressful environments but rarely produces as much yield or oil (Gunasekera 2006a).

1.7 Impacts of Producer Management

Management can affect crop quality, at a gross or detailed level. Jarvis et al. (2008) found that despite many farms producing top grade milling wheat with similar protein content, significant bread making quality differed between individual farms.

1.7.1 Seeding Date

Seeding date has been shown to have a significant impact on crop yield and oil content (Gunasekera 2006a). This impact may be explained by the effect of seeding date on the synchronization between crop developmental stages and typical climatic conditions. In one study, late seeded crops produced plants with lower oil content, while early seeded crops were associated with higher yields. The early seeded crops had longer growing and post-anthesis durations, (which allowed for) greater precipitation

accumulations across these timeframes and the ideal alignment between growing season temperatures and growth stages (Gunasekera 2006a).

In support, Si and Walton (2004) also found oil concentration and seed yield declined with increasingly later seeding dates (from April to July). They concluded that early seeding and cultivars that flower early are integral for optimal canola yield and oil in low rainfall areas.

Earlier seeding dates in Australian climates have been associated with greater yield, WUE, and slightly higher harvest indices. These results may be explained by a number of factors, including greater available soil moisture at seeding, higher transpiration as a percentage of total seasonal evapotranspiration and reduced available soil water at harvest. For example, the sites that were seeded earlier had greater available soil water at seeding, which likely meant early growth and a reduced period of exposed soil. This may have resulted in the increased plant transpiration (as a representation of plant growth) and reduced soil evaporation reported (since transpiration was reported as a percentage of total evapotranspiration which is only comprised of transpiration and evaporation). Furthermore, while the early growth may have allowed the plant time to develop more above-ground plant mass which potentially limited the harvest index values and lowered available soil moisture at harvest, it also may have provided a strong foundation from which the much higher seed yield potentially resulted. Therefore, the low moisture loss to evaporation, along with the early growth and high yield production produced a higher WUE value for early seeded crops (Robertson and Kirkegaard 2005).

Chen et al. (2005) also reported that early seeding dates had a positive effect on seed yield but an inconsistent effect on oil content especially in environments which have a high risk of heat and moisture stress affecting canola crops during sensitive growth

stages. Despite early seeding being associated with low soil temperatures, Chen et al. (2005) found that canola can germinate below a base temperature of 4^{o}C. They also discovered a negative relationship between seeding rate and oil content, with lower oil content corresponding to higher seeding rates.

Seeding date is even more critical in Western Australia because it is timed according to the rainfalls, due to the limited supply of available water. It must be timed so that the crop has enough time to fully mature without excess moisture stress, and avoid extremely high temperatures (especially during sensitive developmental stages) (Farre et al. 2002).

Therefore, although breeding canola to alter length of growth stages may be critical for certain yield or quality parameters, producers' ability to adjust the seeding date, in order to synchronize phenological growth stages with ideal, stress-free weather conditions, can also have a huge impact, especially on yield (Johnston et al. 2002).

1.7.2 Nitrogen Applications

Nitrogen application rates displayed a positive relationship with seed yield (Karamzadeh et al. 2010; May et al. 2010). Seed yield was also positively correlated with several physiological measures, including number of pods per plant, 1000-seed weight, number of pods per main branch and plant height, and negatively correlated with number of sub branches. Seeding rate also affected number of sub branch, number of pods per plant, seed yield and oil yield, but not oil content. This shows the effect a producer can have on a crop by management choices (Karamzadeh et al. 2010). Interestingly, fertilizer did not have an effect on seed weights (Krogman and Hobbs 1975).

Gan et al. (2007) agreed with Karamzadeh et al. (2010) that the rate of nitrogen fertilizer affected the crop physiology, in terms of a slight delay in the first day of

flowering and time until maturity (approximately 1 day for *Brassica napus*). In fact, across the aggregate average of 5 *Brassica* species fertilizer rate had a significant effect on the start of flowering, seed and straw yield, and the harvest index. Nitrogen application also had the greatest impact on the *B. napus* canola (compared to other *Brassica* species) (Gan et al. 2007).

Meanwhile, May et al. (2010) determined location by nitrogen had a significant effect on protein content, which could imply that canola response to variation in environment is partly due to the variation in nitrogen at each location, as well as the conditions that make nitrogen more or less available, such as soil moisture (as result of precipitation levels).

1.7.3 Seeding and Harvesting Management

The popular shift to low or no-till practices amongst western Canadian producers is ideal for the high water requirements of canola, which is able to make use of extra soil moisture that this management practice provides for the crop (Johnston et al. 2002). Direct combining is increasing in popularity, which provides a good alternative to swathing, but must be carried out when the seed has a lower moisture content (than is needed for swathing) and therefore a higher risk of shattering. Canola that is swathed is more likely to be evenly matured, have fewer shattered kernels, but have a greater chance of getting weathered. Swathing prematurely can limit the amount of time for chlorophyll degradation (resulting in undesirable high levels) as can swathing during very hot and dry conditions which prematurely desiccates the seed (Thomas 1995).

1.8 Predictive Modelling for Yield and Quality

In an attempt to maximize profitability for canola producers by providing information on optimal crop management choices regarding location selection, cultivars and seeding date, a number of prediction models have been created. The dilemma with models is that they must always balance the amount of input required with the quality of the output provided. The more sophisticated models may require more input values which must often be measured with special equipment but usually provide more accurate estimates, while simple models have lower input requirements making them easier to use but less accurate.

Models are synthesised around or calibrated to the environment from which the data originate, so they do not necessarily translate well to other environments. For instance, models that were created in Australia are based on heat-tolerant, drought-tolerant canola varieties, have a strong focus on available water supply for the plant and avoiding synchronization of vulnerable growth stages and high temperatures (Farre et al. 2002; Robertson and Kirkegaard 2005). Models that were created in European countries utilize winter canola varieties, which have completely different stress tolerances and are not common in the Western Canadian Prairies.

Due to its relatively recent introduction into Canadian agriculture, there are few long term historic canola data. Furthermore, the rapid pace of canola breeding programs since its arrival in the 1970s has meant that long term data quickly becomes outdated. For these reasons, along with the extensive acreage that wheat and other cereals have historically covered, the majority of crop modelling work that has been done in Canadian agriculture has been on wheat and cereal crops (Jarvis et al. 2008).

The concept of phenology or plant development over time with differing environmental conditions has been explored for decades. Sands et al. (1979) introduced the term P-Day, which refers to physiological days. They recognized that growth rates in potatoes vary according to temperature, and used 7^{o}C, 21^{o}C, and 30^{o}C as the thresholds to separate out the minimum, optimum and maximum temperatures, respectively, for potato development.

More recently, Wilson (2002) created a P-Day index for canola with threshold values of 5^{o}C, 17^{o}C and 30^{o}C, which were determined to be better suited to canola crops. Wilson (2002) used the phenological stages of canola that were described at the time by Thomas (1995) as the basis for defining cumulative P-Day values between specified growth stages.

The APSIM model appears to be successful for predicting canola phenology and yields in Western Australia. The model, as used by Farre et al. (2002), utilized four modules including a canola crop, soil water, soil nitrogen and residue to simulate plant growth and development including water and nitrogen uptake leading to a final yield. APSIM uses a daily time-step process with solar radiation, minimum and maximum temperatures, rainfall, photoperiod, soil moisture and nitrogen data. It assumes a weed, pest and disease-free crop which is only limited by temperature, solar radiation, water and nitrogen supply. While this model was accurate in reproducing the effects of seeding date on the seeding to flowering duration and the final yield across environments with varying rainfall accumulations, it still has some limitations. The initialization for the model requires several soil characteristics that are not easily measured, making it hard to apply to a typical producer field. In addition, while it can predict yield, the APSIM model cannot predict oil content (Farre et al. 2002).

At the other end of the spectrum, the French and Schultz (1984) model is often used by producers and requires very little input data, but requires some improvement on the accuracy of its outputs. The French and Schultz (1984) approach uses seasonal rainfall to predict wheat yields. In an attempt to adapt this approach to canola crops and improve upon the available moisture estimation, Robertson and Kirkegaard (2005) created an improved method which seems to be more robust across environments. They determined the relationships between potential canola yield and water supply with the use of a large dataset from canola crops in New South Wales, and incorporated the soil water at time of sowing and discounted the soil moisture left at harvest. As a result, they improved on the model's accuracy with only the addition of extended rainfall records and an equation, which is data that could be easily accessed and utilized by a producer without additional equipment (Robertson and Kirkegaard 2005).

A model was created based on conditions in Western Canada by Foroud et al. (1992). It was made for an area which generally has low precipitation, low soil moisture, and often requires irrigation. This model uses weather, soil and crop parameters including evapotranspiration and potential evapotranspiration to predict daily crop water use. This prediction is then utilized to create an irrigation schedule with dates and amounts that will allow the root zone to remain at a specific desired moisture level (Foroud et al. 1992).

Jarvis et al. (2008) determined that multivariate, statistical models were more successful than univariate models, since the former could explain nearly half the variation in a wide range of wheat yield and quality characteristics. While Jarvis et al. (2008) believed predictive models have great potential, they could be improved with the installation of more weather stations around the western Canadian Prairies to better delineate the extent of locally wet and dry areas, more knowledge of genotype by

environment interactions, and a more precise knowledge of the timing of phenological development stages.

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2.0 PHENOLOGICAL DEVELOPMENT OF WESTERN CANADIAN CANOLA

2.1 Abstract

Crop management and activities including seeding, fertilizer incorporation, pesticide application, irrigation schedules and harvest methods are all dependent on timing and the convergence of crop growth stage and environmental conditions. However, there is a lack of published research on the phenology of current canola varieties. The objectives of this study were to investigate the phenology of a typical 2009 canola variety through the observation of canola development and the use of P-Days, which measure heat units over time, for specific growth stages. This was done to investigate if the Wilson (2002) P-Day index is still an accurate measure of phenological development for current canola varieties, and if not, attempt to improve on it.

Seven field sites across southern Manitoba, which offered a range of soil and weather conditions, were seeded to variety 5020 or 71-45RR in 2009 and were equipped with a Campbell Scientific or WatchDog weather monitoring system. Throughout the growing season weather data was collected and canola growth stages were identified (according to the Canola Council of Canada's growth stage chart). P-Days$_{(5, 17,30)}$ were accumulated at each site from the seeding date to each observation date and the swathing, harvest, or physiological maturity date. The mean values of the P-Day totals for the observed growth stages ranged from 298 to 815, for six growth stages. The first threshold corresponded to a growth stage at the end of the vegetative period and five corresponded to growth stages throughout the reproductive period.

The comparison between the new P-Day index and the Wilson (2002) P-Day index suggested current canola varieties may reach the flowering stage sooner, have a

longer flowering and pod development period, but reach the stage when seeds in the lower pods are yellow and brown only slightly later. Thus, current varieties may require less time and heat to complete early vegetative growth stages but more time and heat to complete reproductive growth stages and be ready for swathing. In addition, the length of the vegetative stages may be more variable in terms of heat requirements than the reproductive stage.

2.2 Introduction

Seeding, fertilizer incorporation, pesticide application, irrigation schedules and harvest methods are all dependent on timing and the convergence of crop growth stage and environmental conditions (Thomas 1995). Therefore, it is essential to have accurate characterizations of crop growth and development over time, in order to anticipate the correct time to carry out production activities and maximize the efficiency and efficacy of activities to produce crop with high quality and yields.

Since the duration of growth stages has been linked to temperature (Thurling 1974) and high temperatures have been shown to accelerate time to maturity (Yaniv et al. 1995), it is understandable that temperature has been called "the most important environmental factor regulating growth and development of canola in western Canada" (Thomas 1995). Therefore, utilizing a heat unit index in addition to chronological information is necessary in order to understand crop phenology.

Improved accuracy of phenological information and prediction would not only provide more detailed information for timing of production activities, but could also improve outputs of predictive models (for quality or yields). This could also improve crop diagnostic forecasts and assessments through improvements to calculations of

evapotranspiration, as it is preferable to express evapotranspiration as a function of growth stage instead of calendar days which do not take into account the seeding date or weather conditions throughout development (Hobbs and Krogman 1983).

Plant breeders could also utilize updated phenological data to develop varieties with growth stages better aligned to corresponding climatic conditions. Recent findings regarding the impacts of heat and cold stress on crops at specific growth stage (Yaniv et al. 1995; Aksouh et al. 2001) provide an opportunity for breeding efforts to use phenological information to alter the length of certain stages. This would allow for improved alignment between climate and crop development so that sensitive growth stages may avoid extreme temperatures and stressful situations leading to maximized final yield and quality attributes.

For all these reasons, there is a need for more research on canola phenology and the rate of development throughout different stages across varying temperature conditions (Hay and Porter 2006). Such an investigation could provide a comprehensive understanding of the progression of growth stages over variable growing seasons (Shaykewich 1995).

The growth stage chart by Thomas (1995) is used by the Canola Council of Canada (CCC 2011) and was followed in this study (Table 2.1). It outlines the growth stages of the crop from emergence through maturity. If the period for each phase occurs consistently through time or over a known accumulation of thermal time, then time or thermal time can be used as a predictor of canola phenological development.

Table 2.1. Summary of canola growth stages.

Stage		Description of Main Raceme
0		**Pre-emergence**
1		**Seedling**
2		**Rosette**
	2.1	1st true leaf expanded
	2.2	2nd true leaf expanded
	2.3	etc. for each additional leaf
3		**Bud**
	3.1	Flower cluster visible at center of rosette
	3.2	Flower cluster raised above level of rosette
	3.3	Lower buds yellowing
4		**Flower**
	4.1	1st flower open
	4.2	Many flowers opened, lower pods elongating
	4.3	Lower pods starting to fill
	4.4	Flowering complete, seed enlarging in lower pods
5		**Ripening**
	5.1	Seeds in lower pods full size, translucent
	5.2	Seeds in lower pods green
	5.3 [z]	Seeds in lower pods green-brown or green-yellow, mottled
	5.4	Seeds in lower pods yellow or brown
	5.5	Seeds in all pods brown, plant dead

[z]physiological maturity
(Thomas 1995)

In order to describe canola development throughout the growing season most accurately, the measure most consistently related to phenological development should be used. There are several methods to quantify development of various crops over time, including the accumulation of calendar days, Growing Degree Days (GDD), Corn Heat Units (CHU) and Physiological Days (P-Days). Each of these methods has advantages and disadvantages (Shaykewich 1995; Saiyed et al 2009).

Calendar days have been used as a measure of growth and development for their simplicity and practicality. However, rates of plant developmental processes are strongly influenced by temperature (Porter and Gawith 1999) so it is more accurate to measure the

rate of development according to heat units, which are only dependent on temperature, than calendar days, which may correspond to different temperatures each year. For example, June 25 at a certain location may be 15^{o}C one year and 26^{o}C another year. In this case, if growth and development was being measured by calendar days it would incorrectly describe both situations as having the same impact on development. By comparison, measuring with heat units would account for the difference in temperatures and their respective impacts on growth and development. GDD, CHU and P-Days all measure heat accumulation over time, but incorporate base, maximum and minimum temperatures into different formulas.

Corn crops have used CHU and potato crops have used potato-specific Physiological Days (P-Days) for many years, but a lack of research on canola phenology and appropriate canola heat unit indices has led to less crop-specific methods such as Growing Degree Days (GDD) being used for canola crops (and producing inaccurate estimates). While GDD can be useful, they fail to recognize that phenological development is a non-linear function of temperature. As a result, using GDD can produce an underestimation of development at low temperatures and overestimation at high temperatures (Shaykewich 1995). GDD are calculated with daily maximum and minimum temperatures (or daily average temperatures), as well as a base temperature. Base temperatures are incorporated into the equation in order to recognize that plant growth is restricted below certain temperatures, generally between 0^{o}C (CCC 2011) and 5^{o}C (AAFC 2013a) for canola. They are a basic measurement of heat units that take into account the lower temperature limits for plant growth of a non-specific crop (Thomas 1995; MAFRI 2013a).

If GDD > 0

$GDD = T_{AVE} - T_{BASE}$

where:

$$T_{AVE} = \frac{\text{Daily Maximum Temperature + Daily Minimum Temperature}}{2}$$

$T_{BASE} = 5^{o}C$

GDD can be calculated over one or many stages, by daily summations from seeding until the desired growth or phenological stage.

CHU are a heat unit measurement typically used for soybean and corn crops. They take into consideration optimal temperatures specific to corn crops, within which cool or heat stress does not occur. The calculation of these heat units only requires basic daily maximum and minimum temperatures and is shown below (AAFC 2013a).

If CHU > 0 (by $T_{MIN} \geq 4.4$ or $T_{MAX} \geq 10$)

$$CHU = \frac{1.8\,(T_{MIN} - 4.4) + 3.33\,(T_{MAX} - 10) - 0.084\,(T_{MAX} - 10)^2}{2}$$

Where:

T_{MIN} = Daily Minimum Temperature
T_{MAX} = Daily Maximum Temperature and

A more sophisticated model that considered the duration of temperatures throughout the day and night along with the variable rates of plant development that occur at different temperatures, was the P-Day model (where the P stands for physiological) (Sands et al. 1979). The temperature parameters of this model can be adjusted according to the crop of interest, with Sands et al. (1979) using $7^{o}C$, $21^{o}C$ and $30^{o}C$ for the baseline, optimal and maximum temperature (within the optimal growth range), respectively for potato crops. Several different thermal time units for canola have previously been tested by Wilson (2002), who concluded that the weighted P-Day unit with minimum, optimum and maximum temperatures (within the canola growth range) of $5^{o}C$, $17^{o}C$ and $30^{o}C$, respectively, was the most suitable for estimating canola development. Using the

temperature parameters of Wilson (2002) on the model by Sands et al. (1979), the weighted P-Day formula was used:

$$\text{P-Days} = \frac{1}{24} \times (5 \times P(T_1) + 8 \times P(T_2) + 8 \times P(T_3) + 3 \times P(T_4))$$

where:

$T_1 = T_{MIN}$

$T_2 = \frac{(2 \times T_{MIN}) + T_{MAX}}{3}$

$T_3 = \frac{T_{MIN} + (2 \times T_{MAX})}{3}$

$T_4 = T_{MAX}$

$P = 0$ if $T < 5$

$P = k \times \{1-[(T - 17)^2/ (17- 5)^2]\}$ if $5 \leq T > 17$

$P = k \times \{1-[(T -17)^2/ (30 -17)^2]\}$ if $17 \leq T > 30$

$P = 0$ if $T \geq 30$

k is a constant and a scale factor set at 10.

Each of these daily values for any heat unit can be accumulated over a specific amount of time (ex. seeding date until date of harvest) to represent the heat units required to attain a specific growth stage, such as seeding to maturation. Estimates of CHUs for corn varieties are presented in seed guides (as assigned by seed production companies) to advise producers on the approximate heat requirements for the crop to reach maturity (MAFRI, MSGA and the Manitoba Co-operator 2013). These are used in combination with estimations of the probability of achieving a certain (range in) quantity of CHUs in various farming regions (Shaykewich and Blatta 2013) to assist producers in their selection of next year's crop or assessing the past growing season (AAFC 2013c).

The study by Wilson (2002) was the most recent assessment of canola phenology available, so these temperatures and P-Day thresholds were compared against the new

thresholds created in this study, in order to verify the values determined were within an acceptable range. Understandably, the varieties used in Wilson's field study in 1999 and 2000 may have different phenological development rates than varieties prevalent in 2008 and 2009. Therefore, the current study also investigated the accuracy of the Wilson (2002) P-Day model for current canola varieties and compiled P-Day thresholds based on the average number of P-Days required across varieties, soil type and location to reach several of the phenological stages identified by Thomas (1995). This was done in order to update past phenology information using current canola varieties.

The objectives of this study were:

a) To investigate the phenology of typical 2009 canola varieties (5020 and 71-45RR) through the observation of growth and development along with corresponding accumulation of heat units over time via P-Days
b) To determine if the P-Day index created by Wilson (2002) is still an accurate measure of phenological development for current canola varieties, and if not, improve on it

2.3 Materials and Methods

2.3.1 Site description

Seven field sites across southern Manitoba located near Portage, Oakville, Jordan Corner, Balmoral, Rathwell, Carman and Rosebank were used for this study. These locations represented a range of soil conditions and variety of weather conditions (MAFRI 2013b).

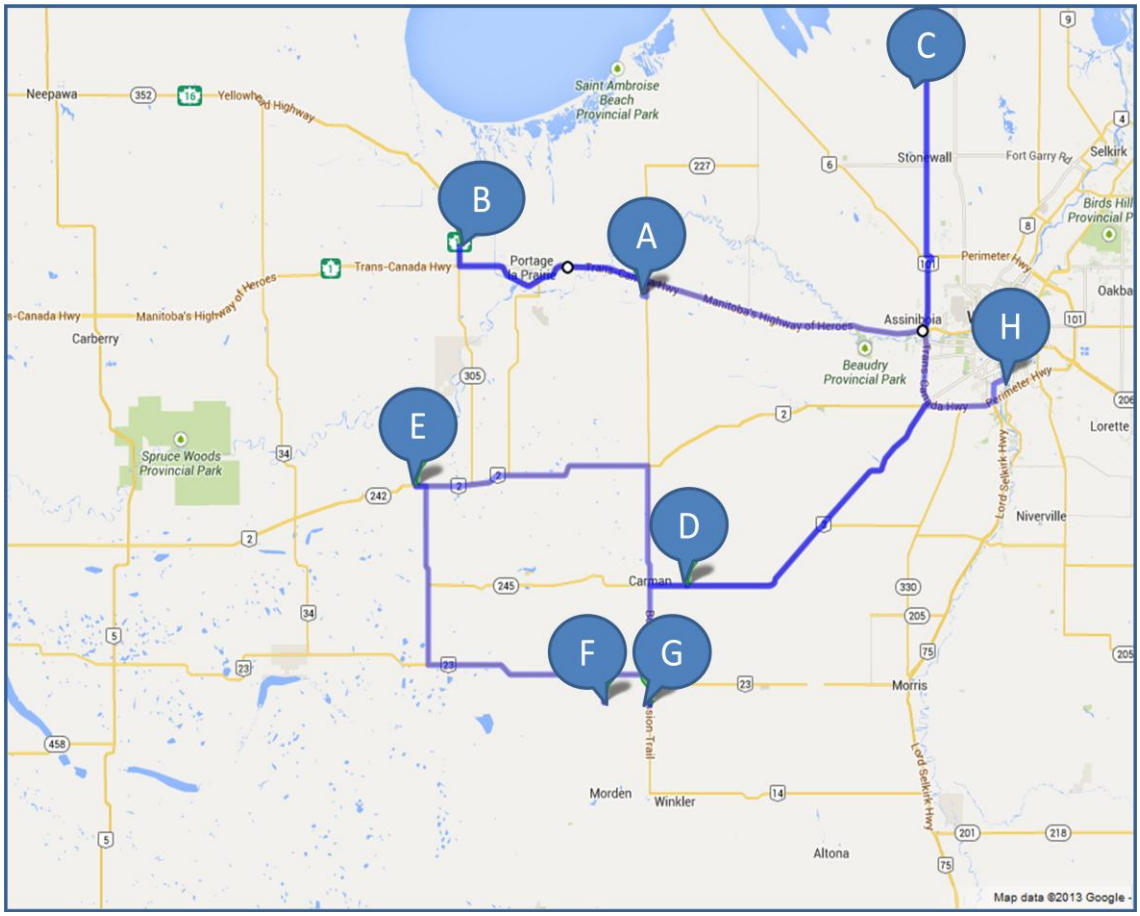

Figure 2.1. Approximate locations of the seven field sites in southern Manitoba.

KEY:
Location A = Oakville site, MB
Location B = Portage la Prairie site, MB
Location C = Balmoral site, MB
Location D = Carman site, MB
Location E = Rathwell site, MB
Location F = Rosebank site, MB
Location G = Jordan Corner site, MB
Location H = University of Manitoba in Winnipeg, MB

Each site was either a large-scale plot or a 160 acre field located within a two hour drive of the University of Manitoba, for ease of frequent monitoring. Each site was available through collaboration with PioneerHybrid, Bayer, or Monsanto, and several producers. In some cases, the collaborating companies also had weather stations on or

very close to the sites and provided data from those stations to verify the weather data collected with the weather monitoring equipment used in this study.

Soil type varied across sites, with soil textures generally ranging from medium to fine (Table 2.2).

Table 2.2. Study site locations and information.

Sample ID	Variety	Collab-orating Company	Seeding Date	Swath Date	Nearest town	Long (N)	Lat (W)	Surface Soil Texture[a]
2RBY	5020	Pioneer-Hybrid	20-May-09	23-Sep-09	Rosebank	49.34	98.12	Medium with a bit of fine
3TRY_5020	5020	Pioneer-Hybrid	23-May-09	30-Sep-09	Rathwell[b]	49.66	98.58	Medium with a bit of fine
Balmoral_5020	5020	Bayer	30-May-09	7-Sep-09	Balmoral	50.22	97.26	Medium with a bit of moderately coarse
Carman_5020	5020	Pioneer-Hybrid	21-May-09	18-Sep-09	Carman	49.49	97.94	Moderately Coarse and Medium with some fine
Portage_5020	5020	Bayer	22-May-09	1-Sep-09	Portage	50.00	98.46	Medium with some fine and moderately coarse
Oakville_7145	71-45RR	Monsanto	24-May-09	17-Sep-09	Oakville	49.93	98.01	Fine with a little medium and moderately coarse
Jordan Corner	5020	Monsanto	21-May-09	17-Sep-09	Roland[c]	49.34	98.03	Medium and Fine

Long (N) = Longitude
Lat (W) = Latitude
[a]Information from AAFC 2013b
[b]The tipping bucket was at Rathwell, the temperature data was used from PioneerHybrid's Treherne site, which was 2 kilometers away
[c]The site was close to the intersection of highway #3 and highway #23, which is commonly known to nearby residents as "Jordan Corner". It is also 4.5 kilometers away from Roland.

2.3.2 Variety Information

Six of the seven sites were planted with 5020, a widely recognized variety often used by various seed companies as a standard in yield and quality trials (MSGA, MAFRI and the Manitoba Co-operator 2009). The Oakville site was planted with 71-45RR, a

Round-Up Ready™ variety that was also popular in 2009. Variety 5020 has been available to producers since 2004 and 71-45RR has been available since 2006, so they were both well-established in 2009. They are both hybrid varieties, which accounted for the majority of canola varieties grown in western Canada in 2009 (DeClercq 2008), but 5020 is produced by Bayer and 71-45 RR is produced by Monsanto.

2.3.3 Meteorological Monitoring

The field sites were used for both the observation of canola growth and the collection of weather data, which was used to link the plant growth and development to the accumulation of heat units over time.

2.3.3.1 Weather Monitoring Equipment. The weather-monitoring equipment included two Campbell Scientific weather stations, two WatchDog weather stations and three cooperating company weather stations. Each type of weather-monitoring equipment was chosen for a field site based on the proximity to a complimentary weather station (causing the Campbell Scientific and WatchDog stations to be set up at field without nearby cooperating company weather stations), the lay-out of the plot or field (space availability, proximity to obstructions or potential farm equipment traffic), and in agreement with cooperating companies, farmers, and another study using data from the two Campbell Scientific weather stations (where applicable). The Campbell Scientific weather stations were set up at the Portage and Oakville sites and the WatchDog weather stations were set up at the Balmoral and Jordan Corner sites. The Carman, Rosebank and Rathwell sites all had cooperating company weather stations nearby to provide temperature data.

All weather equipment was set up on level ground, at the edge of the field according to specifications given by the Campbell Scientific manuals (Campbell Scientific, Inc. 2013). The Campbell Scientific weather stations measured air temperature

and humidity with a radiation shielded probe (CS 500, Campbell Sci., Logan, Utah) at a height of 1.75 m. The Campbell Scientific CR1000 dataloggers logged measurements for each sensor every 10 seconds to produce both hourly and daily averages, and accumulated totals for precipitation.

The WatchDog weather stations (model 900ET) included a radiation shielded temperature and humidity sensor (Spectrum Technologies Inc., Aurora, IL). Instantaneous readings were logged every 10 minutes.

2.3.3.2 Spring Calibration of Weather Equipment. Before the weather monitoring equipment was set up at the field sites, it was tested to ensure it was providing accurate, reliable information. The Campbell Scientific and WatchDog weather stations were set up outside and collected test sets of data, to be compared against each other. These test runs of the instruments were carried out at the Point, a section of land used for research studies at the northeast corner of the University of Manitoba campus. These calibrations took place in early May, before the field sites were seeded, and again after the equipment was removed from the field sites (after the field sites were swathed or harvested). Both times, the two WatchDog and two Campbell Scientific weather stations were set up in a north-south line, parallel to the field's edge for more than ten days of measurements, which were recorded hourly and daily on the Campbell Scientific weather stations and every ten minutes on the WatchDog weather stations. The data was then aligned so that the time stamps matched from the all sources for evaluation.

The temperature data was compared by determining the maximum difference between any two of the four data points, determining the standard deviation, mean value and coefficient of variation across the data points from each of the weather stations.

The temperature data was very similar between the four weather stations. Except for two days when the greatest differences between any of the two recorded temperatures were 1.00^{o}C and 1.34^{o}C, all other differences between any two temperatures recorded were less than 1^{o}C. Naturally, this also produced very low coefficient of variation values, nearly all of which were below 0.2, except for 3 slightly higher coefficient of variation values (which were 0.23, 0.53 and 0.69). Since the temperatures were so similar, the equipment was deemed sufficiently accurate for determining differences in heat unit accumulation between the field sites.

2.3.3.3 Growing Season Weather Monitoring. The field sites were visited weekly or biweekly to collect data from the datalogging systems and to ensure the sensors were working and collecting accurate data. The WatchDog weather stations were set to hold data for up to 21 days. The Campbell Scientific weather stations could log and store weather data for the entire growing season, if needed.

Aside from data collection and observations, visiting the sites included checking on the instruments, ensuring that the equipment was level (especially the pyranometer), properly aligned (particularly the anemometer), the battery was charged and the station was intact (so that accurate data would continue to be collected). If the uploaded data had any irregularities, the program would be resent to the datalogger and a short test set of data was collected to confirm the equipment was working well again.

When the ground became drier, cracks formed and caused the weather station at the Oakville site to lean, so it had to be re-leveled.

The weather stations were taken down when the crop had been swathed or physiological maturity had been reached (and therefore it had surpassed all the growth stages). Although weather data collection and observations past the final growth stage

was not necessary for this study, it is understood that weather data collected during and after swathing date could be useful for other research. Often canola is cut when the chlorophyll content is higher than desired, but leaving the swath for a week or two will allow this to break down, leaving a much lower content (Thomas 1995). If the chlorophyll content is too high it will not meet the specifications for the top grade, and therefore would not be included in this study. Often management logistics play a fairly large role in deciding when the canola is combined, not just the weather. There are other down grading factors that can affect canola after it is cut, such as seeds rotting or molding (or the pods can shatter causing a loss of yield), but since these happen after the crop has been cut, the plant (above where it was cut) is no longer alive and therefore it is assumed that factors other than the weather will be more important.

2.3.3.4 Fall Calibration of Weather Equipment. After the weather equipment was used throughout the growing season, the equipment was taken down, brought back to the University of Manitoba and set up again at the Point (on the northeast corner of the University of Manitoba campus), the same location the spring calibrations took place. Weather data was collected for just over three weeks by the two WatchDog and two Campbell Scientific weather stations, compiled and compared against each other.

Temperature data were (again) very similar across all four weather stations, especially between the two WatchDog weather stations and between the two Campbell Scientific weather stations. Across all four weather stations, the range in average temperatures remained below 1^{o}C across all days measured, except for the day the stations were taken down (which is the likely the cause of this discrepancy).

The variation between minimum temperature values was the greatest amongst negative temperatures (but still not a concern with maximum ranges between any two

data points of 1.03, 1.07 and 1.07). However, since the growing season did not include any of these values, that is not a concern for the data that was included in the field study. Outside of one outlier amongst the maximum temperatures (September 30, 2009) and the day that the weather stations were taken down, the maximum range between any two temperatures measured was always below 1.4^{o}C (with only seven times when the range amongst minimum, maximum or average temperatures exceeded 1^{o}C). This translated into low coefficient of variations across the average, minimum and maximum temperatures measured.

2.3.4 Weather Data and Growth Stage Analysis

All the weather data collected on different dates were organized into one dataset, and then converted into daily values, if necessary. While Campbell Scientific weather stations recorded data in both hourly and daily values, the WatchDog weather stations recorded data every ten minutes, so these values were compiled into hourly and then daily values. The daily data were checked for missing values (when the stations were shut off to upload the data, when tests were run with the tipping buckets or they stopped recording data) and irregular data (such as in the case of equipment not working properly or being moved by a storm or person). Missing or irregular data was filled in with weather data from one or two nearby (collaborating company weather stations and Environment Canada or Canadian Wheat Board) weather stations, with priority given to the stations within closest proximity.

The seeding and swathing, harvest or physiological maturity dates for each site were used to mark the beginning and end of the growing season weather data for each site. In some cases this meant filling in a few days of data between seeding date and the date weather equipment was set up, and in one case (the Carman site) this meant filling in

a few days of data between the weather equipment being taken down and the crop being straight-cut. Again, this missing data was filled with collaborating company weather stations and Environment Canada or Canadian Wheat Board weather stations.

The daily minimum, maximum and average temperature values were then used in the P-Day formula described in the Introduction section to calculate a P-Day value for each day. The temperature parameters of 5^{o}C, 17^{o}C and 30^{o}C were used in the P-Day formula for the minimum, optimal and maximum temperatures. Then P-Day values were accumulated over the course of crop development from seeding date until swathing, harvest or physiological maturity dates.

The field observations were used to identify the growth stage, according to the descriptions in the growth chart by Thomas (1995) and were listed by the numeric growth stage (e.g. 3.2). The growth stages for each observation date were then paired with the date listed in the weather data for the sites, and its corresponding P-Day total (which was accumulated from seeding until each observation date). This was done for each site and shown in Appendix 2.

All of the accumulated P-Day totals corresponding to each of the growth stages were averaged across the sites. These mean values for each growth stage became the accumulated P-Day thresholds for each of the growth stages observed, and together formed the updated P-Day index. The differences between the expected P-Day total values (according to Wilson 2002) and observed total P-Day values (as determined by the field study) for each growth stage were also calculated when possible (if the growth stages described in Wilson (2002) had also been observed in the field study).

2.4 Results

2.4.1 Factors Affecting P-Day Values

As a product of the intensity and duration of temperatures and the number of days over which they are accumulated, the P-Day values reported in the field study were affected by seeding dates, growing season length and temperatures throughout this period. Seeding dates ranged from May 20 to May 30 and were slightly later normal due to spring weather conditions (MAFRI 2009). Much of the prairies experienced colder than average temperatures March, April, and May, which delayed seeding in many areas of the prairies, especially in Manitoba, which also had excess moisture in April. This also resulted in low P-Day accumulations in May. The 2009 growing season continued to produce fairly cool temperatures in June and July, reached fairly average values in August, and then high maximums in September (Tables 2.3 and 2.4).

Table 2.3 Monthly mean Portage la Prairie daily temperature values (°C).

Month	Maximum Temperature (°C)		Minimum Temperature (°C)		Average Temperature (°C)	
	2009 Data	Climatic Normals	2009 Data	Climatic Normals	2009 Data	Climatic Normals
March	-3.0	-0.6	-12.4	-10.6	-7.7	-5.6
April	6.9	10.4	-1.6	-1.9	2.7	4.3
May	15.1	19.3	2.4	5.5	8.8	12.4
June	17.1*	23.4	5.8 *	10.8	11.2*	17.1
July	22.6	26.3	12.1	13.6	17.4	20.0
August	23.1	25.1	13.2	11.8	18.2	18.5
September	24.6	18.4	11.3	6.3	18.0	12.4

*The value displayed is based on incomplete data

Data source: Environment Canada 2013a; Environment Canada 2013b

Table 2.4 Monthly mean Portage la Prairie total daily precipitation (mm)

Month	2009 Data	Climatic Normals
March	40.3	26.8
April	59.0	34.5
May	64.8	51.7
June	68.6*	80.9
July	76.0	72.8
August	42.8	71.1
September	18.8*	58.5

*The value displayed is based on incomplete data
Data source: Environment Canada 2013a; Environment Canada 2013b

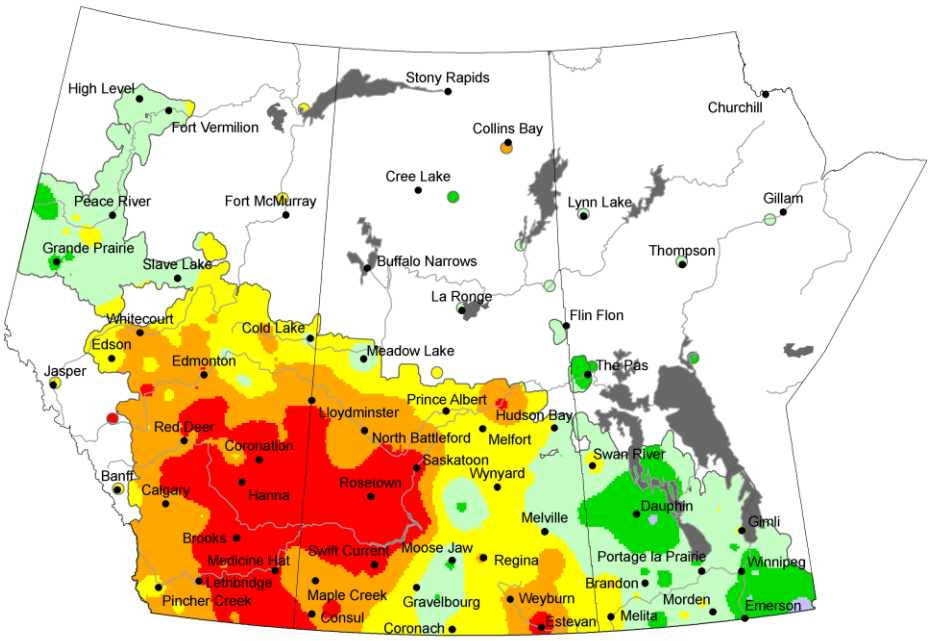

Figure 2.2 Percent of Average Precipitation (Prairie Region) from March 4 to June 1, 2009.
Map source: AAFC 2009

The frost-free period extended into autumn, with the first negative temperatures appearing at the end of September (September 29, 2009) at the Portage, Miami (near the Rosebank and Rathwell field sites) and Stony Mountain (near the Balmoral field site) Environment Canada weather stations and not until early October (October 8, 2009) at the Carman weather station (Environment Canada 2013a, Environment Canada 2013b).

2.4.2 Assessment of P-Day Totals for Growth Stages

When field sites were visited, notes about the growth stages of the canola crops were recorded and captured by photo. This information along with the date on which it was collected was used in the creation of a new P-Day index (when paired up with corresponding P-Day totals).

The number of P-Days accumulated over each growth stage, at each of the field sites is given in Table 2.5, as well as the comparison of these values to the P-Day thresholds stated by Wilson (2002). Depending on the field site, there were ten or eleven observation dates at each field site throughout the growing season. The observations started either before the crop had emerged or at the cotyledon stage and continued until the crop was at least gold and green and occasionally until full senescence. The growing season P-Day totals varied from 788 to 974. The observations captured all the stages listed in the P-Day index by Wilson (2002) and most of the stages listed in Thomas (1995) except stages 2.1, 3.3 and 5.3.

There were some variations between field sites in the number of P-Day totals at each growth stage, as expected. Carrying out the field study over a variety of locations with different soil types, weather conditions and seeding dates are all factors that may have caused these differences, along with potential genotype by environmental interactions. Mean accumulated P-Day thresholds were calculated from the P-Day totals of as many field sites as possible, and had corresponding growth stages. The means for growth stages 4.2, 4.3, 4.4 and 5.2 were composed of seven (P-Day total) values from field sites, the mean for growth stage 5.4 was produced from six values and the mean for growth stage 3.2 included only three field sites but was cross-referenced with the values from Wilson's index to ensure that it was realistic or potentially correct.

The new P-Day index that was the combination of these mean values and included six growth stages, with a strong focus on the reproductive period. The reproductive stages spanned from phenological stage 4.2 (many flowers being open) to phenological stage 5.4 (seeds in lower pods being yellow or brown) (Thomas 1995). The inclusion of the late phenological vegetative stage 3.2 (defined by the flower cluster raised above the level of rosette) (Thomas 1995) was beneficial because it was the only pre-reproductive stage included in the index. The P-Day thresholds determined in this study are reported with corresponding growth stages and the descriptions given in Thomas (1995) in Table 2.6

Table 2.5 P-Day values accumulated from seeding to date of observed growth stages for each field site.

Variety	Cumulative P-Day Values								
	5020	71-45RR	5020	5020	5020	5020	5020	Mean	Wilson 2002
Field Sites	Portage	Oakville	Jordan Corner	Balmoral	Carman	Rosebank	Rathwell	P-Day Values	Values
Growth Stages[†]									
0.0									
1.0	82.5	77.3	96.4			102.1	82.5	88.1	
2.1				109.6					
2.2	131.1	129.8		109.6				**123.5**	**139.7**
2.3	169.3	168.3	189.3	155.7	191.2	191.4	169.0	176.3	
2.4	205.7	204.7	223.2		221.6	227.0	207.7	215.0	
2.5				253.1					
3.1	299.7							**299.7**	**299.0**
3.2		301.1		288.9			303.6	**297.9**	**359.8**
3.3									
4.1			317.9		314.6	320.0		317.5	
4.2	397.5	401.1	423.9	373.0	417.3	421.8	403.0	**405.4**	**419.2**
4.3	463.1	467.3	492.6	488.3	482.3	488.4	470.2	**478.9**	**478.6**
4.4	585.3	592.8	618.7	603.3	604.5	612.2	591.1	601.1	
5.1	643.8	649.3	673.0	666.2	656.9	668.6	645.5	**657.6**	**528.7**
5.2	714.4	721.6	745.4	778.4	727.8	739.6	717.1	**734.9**	**583.3**
5.3									
5.4	788.1	803.2	836.8		818.8	833.3	807.8	**814.7**	**757.5**
5.5			973.8					**973.8**	**835.9**

[†]According to the Canola Growth Chart by Thomas 1995

Table. 2.6 Accumulated P-Day values used for growth stage estimation.

Growth Stages	Description†	P-Days
3.2	Flower cluster raised above level of rosette	298
4.2	Many flowers opened, lower pods elongating	405
4.3	Lower pods starting to fill	479
4.4	Flowering complete, seed enlarging in lower pods	601
5.2	Seeds in lower pods green	735
5.4	Seeds in lower pods yellow or brown	815

† Taken from Thomas 1995

2.4.3 Comparison between old and new P-Day Indices

The new accumulated P-Day thresholds differed from those determined by Wilson (2002), suggesting there could be differences between the varieties used by Wilson (2002) and those used in the current study. The Wilson (2002) study included older varieties (Quantum and 2273) which have since been replaced with higher-yielding hybrids, such as 5020 and 71-45RR (which were not available to producers in 1999). The difference between P-Day thresholds of the current study and those in Wilson (2002) for certain growth stages suggested that there has been a shift in the durations of specific growth stages between the older and current varieties. The current varieties reached growth stages 3.2 and 4.2 in fewer P-Days than the older varieties, but reached growth stage 4.3 in a similar number of P-Days (for both current and older varieties). Interestingly, the current varieties appeared to require more P-Days to reach growth stages 5.2 and 5.4. Thus, the current varieties seemed to require fewer heat units for the early vegetative growth stages but more heat units during the reproductive stages and to reach complete maturity (Figure 2.3).

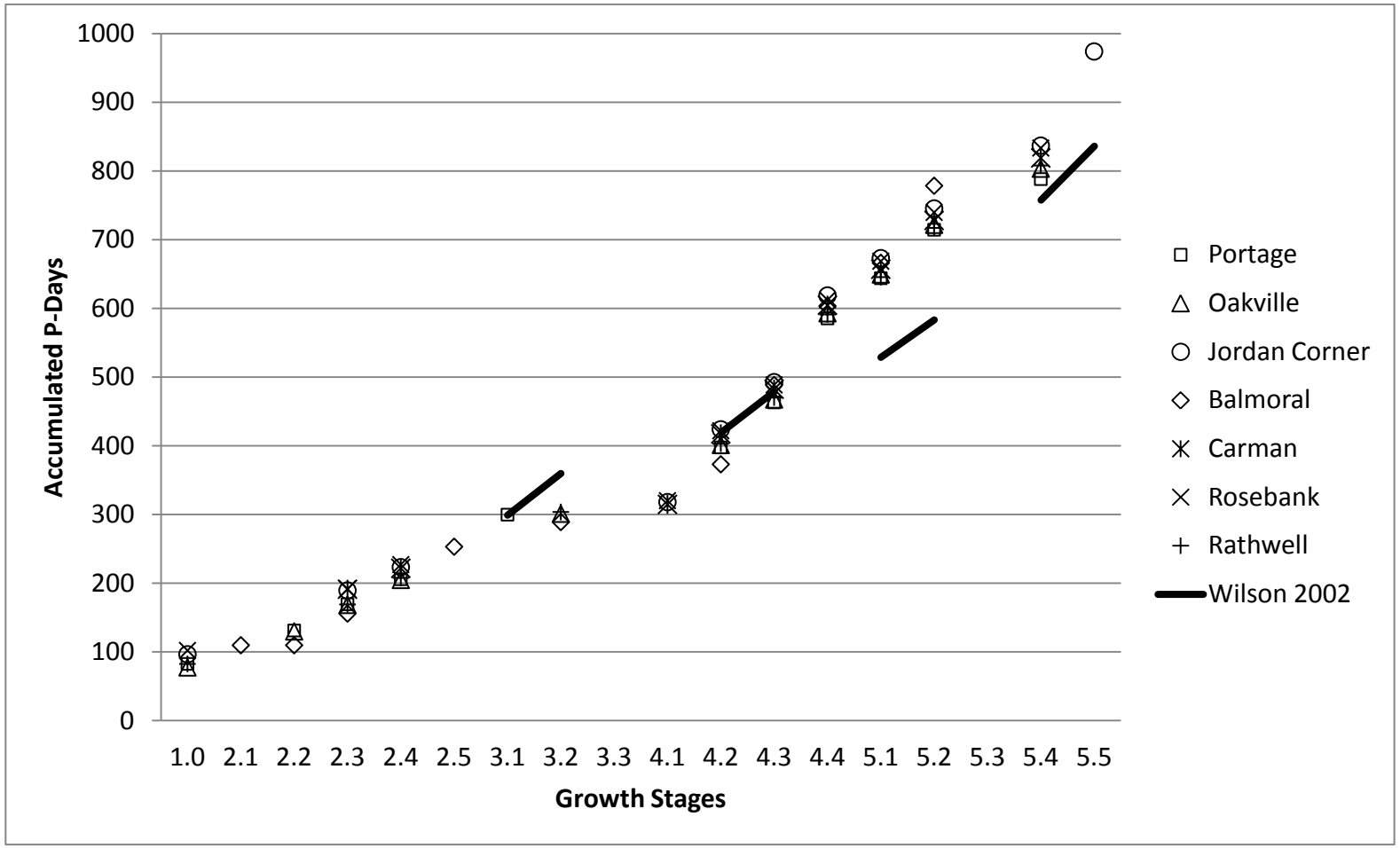

Figure 2.3. Observed growth stages and accumulated P-Days from field sites in comparison to Wilson (2002).

2.5 Discussion

2.5.1 Phenology of current canola varieties

There appeared to be little difference in P-Day totals for growth stages between variety 5020 and variety 71-45 RR data (although it is understood that there was only one crop of 71-45 RR grown). There were also consistent P-Day totals for growth stages between the field locations with varying soil and weather conditions. The most notable difference between P-Day thresholds for growth stages may have been due to seeding date. Balmoral was seeded on May 30, six to ten days later than the other sites, and ended up having P-Day thresholds for various growth stages at the extreme (higher or lower) end of the range in values. It is soil temperature, rather than air temperature, which primarily determines the rate of seed germination and seedling emergence. Differences in soil temperature and moisture between the study sites will affect this first stage of canola development. These differences could result from variation in soil properties, stubble management, tillage practices and drainage strategies. Even the orientation of the field relative to prevailing winds, nearby water bodies, shelterbelts, seeding rate, row spacing and previous crop can affect the spring soil temperature.

The crops at all the field sites followed the regular progression from one growth stage to the next, passing through early growth stages fairly rapidly (since less physical change was required for each of the earlier stages). Early development progressed so quickly that several stages could occur between observations or with observations from only a few sites. This limited the number of early growth stages included in the P-Day index. It required a greater accumulation of P-Days (and therefore a greater number of days) for crop to progress through the reproductive period. The cooler temperatures throughout June and July in 2009 allowed

development to occur at a moderate rate, while high temperatures in September (especially the high minimum temperatures) allowed most field sites to accumulate the necessary P-Days to reach maturity.

Generally, there was moderate variation in early growth stage P-Day totals between field sites, low variation (in P-Day totals) at the mid-growth stages (except for stage 4.2) and greater variation towards the end of the growing season near Stage 5.2 and 5.4. For example, there was quite a bit of variation in P-Day totals for stage 2.3 (with a maximum range between any two values of 35.8), which may be partially be due to crops still being heavily influenced by their seeding dates, and partially due to low total values making a moderate difference appear larger relative to the total value. Meanwhile, the maximum ranges in P-Day values for stages 3.2 and 4.1 were 14.7 and 5.5, respectively.

There was a fairly large gap between some of the values listed for phenological stage 4.2 (50.9 P-Day values), with the outliner belonging to the late seeded crop (by nearly 25.0 P-Day values). This large range in values may be partially due to the definition of the stage being "many flowers opened, lower pods elongating" (Thomas 1995) which applies to many observations (as oppoased to the stage, which as limited to only the first flower open) and is very inclusive (ranging from $\geq$2 flowers open until the lower pods start to fill). Since the flowering period lasted a long time there were also more opportunities for observations to be made, during the beginning, middle and end of the stage, creating a great spread in P-Days reported.

Toward the end of the growing season, when average to above average temperatures prevailed, the crops approached completion and completed development (stages 5.2 and 5.4) over another wide range of P-Day totals. These totals may have

been variable between sites because of the impact varying soil moisture levels may have had on crop maturity depending on moisture contents (which may have affected enzyme activity). It may also be the result of a combination of factors, such as a case where high temperatures caused huge P-Days accumulations over a short time, field sites were only being checked every week or two, and the timing between site visits and growth stages aligned so that observations were made at the beginning of one growth stage and the end of another, producing a greater spread in corresponding P-Day values (as opposed to all values corresponding to the middle of the growth stage). For example, the Balmoral site accumulated 112.2 P-Days between the two site visits (August 19 and September 1), producing an average P-Day value for stage 5.1 (assessed during the middle of the growth stage) and a high P-Day value for the growth stage 5.2 (assessed toward the end of the growth stage). Alternatively, this could be due to the last two growth stages being difficult to distinguish between, since the threshold to be surpassed is whether or not all pods are brown and the plant being dead.

The higher variation (with a maximum range between any two sites of 48.8 P-Day values) that occurred in the final growth stage (5.4) may also be the result of producer management. Producers who swath the crop will cut it sooner, while those who choose to straight-cut are more likely to leave the crops standing in the field long enough to reach growth stage 5.5.

In terms of calendar dates, the late seeding left crops emerged in the first two weeks of June and began flowering in early July. The canola crops flowered while much of the area had below normal temperatures, which likely contributed to the flowering stage lasting for several weeks and ending between the first and second week of August (both because it took longer to accumulate the necessary heat units

and because low temperatures are favourable for canola). Interestingly, even though all the crops were seeded relatively late, they all managed to reach maturity by mid-September, before the end of the growing season.

Overall, (based on the field sites in this study) the length of the vegetative stages appeared to be more variable than the reproductive stage. Some crops emerged faster than others and appeared to vary in plant densities, but by full flowering they all appeared to be at a relatively similar stage in development. The fields with lower plant density seemed to have adjusted to the extra space by growing additional branches, while the higher density crops had more plants with fewer branches.

In general, the observations during the field study emphasized how quickly development can occur, highlighting the importance of carrying out as many visits to the field site as possible. While visiting sites weekly or biweekly did provide enough data to adequately describe canola development, more visits would have provided better precision on growth stage determination and data for more growth stages. It would be recommended in a future study to visit the sites daily to ensure the exact date of each stage in observed, and to include as many field sites as possible for additional data points. It may also be useful to include several popular varieties which are being used across the industry (as 5020 and 71-45 RR were at the time of the field study), possibly even from several different agriculture companies, in order to get a more complete representation of the phenotypic expression of the varieties available at the time.

2.5.2 Comparison of P-Day indices

Determining means of the P-Day totals (from seeding until date of observation) from each field site, for each growth stage led to the creation of new set of P-Day thresholds for several growth stages, which together made up a new P-Day

index. This new index was intended to depict the growth patterns of current canola varieties (when grown in southern Manitoba). A comparison to the P-Day index by Wilson (2002) suggests that breeding efforts to maximize yield may have shifted canola phenology. The specific difference in P-Day totals for growth stages between the P-Day index created in this study and the index created by Wilson (2002) offer insight into how varieties may have changed over the last decade and perhaps why the current varieties are so successful. The difference in P-Day thresholds for growth stage 5.2 of the current index from the P-Day threshold of the Wilson (2002) index was 151.6 P-Days. This is a notable change that suggests the newer varieties take more time to fill and may be partly the reason that canola yields have been increasing.

The current varieties are not only blooming for a longer time, but also reaching maturity slightly later. When swathing is the harvest method, the crop can be cut when it is still quite green, however straight-cut crops must be fully mature earlier in the season. Due to shattering issues, many farmers prefer to swath their crops. A longer growing season requiring greater P-Day accumulation for canola to reach maturity will not facilitate any type of shift towards straight-cutting.

These differences between the Wilson (2002) P-Day thresholds and those observed in this study suggest that updating the P-Day index on a regular basis may be beneficial. The current study determined P-Day thresholds for growth stages 3.2 and 4.2 were fairly similar to those given in Wilson (2002) (with differences of 61.9 and 13.8 P-Days, respectively), while P-Day thresholds for growth stage 4.3 were nearly identical (0.3 P-Day difference). The lack of difference between the P-Day thresholds for different growth stages of variety 5020 and variety 71-45 RR also suggests that the difference between current varieties (5020 and 71-45RR) is not as great as the difference between current varieties and older varieties. This could imply that current

varieties all have longer flowering and seed-filling periods due to successful breeding programs for higher yields.

2.6 Conclusion

This study was conducted to determine if the P-Day index created by Wilson (2002) was still an accurate measure of phenological development for current canola varieties. The observed differences between the P-Day index by Wilson (2002) and the updated index study suggest that breeding may have improved canola varieties in only ten years. This is indicative of the relatively fast pace that canola varieties appear and disappear on the marketplace. The P-Day thresholds (of the current study) were lower for the vegetative stages, equal at the beginning of reproduction and greater at the middle of reproduction, in comparison to those by Wilson (2002). This could suggest that there have been alterations in the plant biology to focus less energy on the vegetative stage and more on the reproductive stage. This alteration could provide (the plant) more time for seed development, oil production and the development of specific fatty acid profiles. In additon, the observed variability in the length of the vegetative stage may suggest an emphasis on seed production and yield rather than additional structural support.

The rapid turnover of canola cultivars and changes in the length of critical growth stage suggests that an understanding of the phenology of current canola varieties is important. Knowledge of canola heat unit requirements is necessary in order to model its growth and development and for knowledge needed to crop optimize production and management activities. This information would facilitate the trend towards precision farming and could be used to adjusting the timing of nutrient or chemical applications, as well as optimize timing to scout crops and plan for harvest timing and methods. Furthermore, this information could help characterize

current varieties for future comparisons and for various research purposes, such as predictive modeling studies.

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3.0 QUANTIFYING WEATHER EFFECTS ON CANOLA QUALITY

3.1 Abstract

Growing season weather affects canola quality parameters and understanding these effects could lead to reliable canola quality predictions prior to the end of the growing season. The objectives of this study were to quantify the impact of environment, genotype and genotype by environment interaction on canola quality in western Canada and use these relationships to construct predictive models. Canola samples from a seven-site field study, collaborating companies' field sites and a selection that graded Canada No.1 from the 2008 and 2009 harvest surveys were analyzed for total oil content, protein content, oleic, linoleic, linolenic, and total saturated fatty acid content and iodine value. Univariate and least square means tests determined that oil and protein content had an inverse relationship, chlorophyll content had the largest variance, and glucosinolates, iodine value, oleic, linolenic and saturated fatty acids content were affected by year. Variety had an effect on oil, chlorophyll and the fatty acid profile, while latitude had a non-significant impact.

Weather data from the field study, collaborating companies, CWB, or Environment Canada weather stations closest to the canola sample locations were compiled. Observed and calculated weather parameters measured across developmental stages (designated by six P-Day thresholds) were used along with quality parameter values (for each of the 247 canola samples) in PLS analysis to create nine predictive models. The final models explained from 7 to 49% of the variation in individual quality parameters. The models for saturated fatty acids, glucosinolates and iodine value models explained the highest amount of variation and the chlorophyll model explained the least. Oil content was positively impacted by

increased duration of temperatures below 11-14^{o}C throughout the reproductive stage, while protein was positively correlated with cool temperatures at early flowering and high temperatures throughout pod and seed development. Chlorophyll was strongly impacted by moisture balance throughout the early to mid reproductive stages and glucosinolates content was affected by conditions that impacted nutrient availability. The total saturated fatty acid content was positively correlated with cool late vegetative and early reproductive stages. Moderate weather impacts on individual fatty acid contents reflected breeding success and the complex interactions amongst each other and total oil content.

This research could help producers pick canola varieties most suitable for the weather conditions in their area and maximize their crop quality by adjusting managment strategies to align growth stages with preferred weather conditions. It could also provide a useful tool to export merchants to share with worldwide customers wanting a preview of the crop quality before it is even harvested.

3.2 Introduction

Canola is a Canadian product of successful breeding for low erucic acid and low glucosinolates (double-low) rapeseed. Canola improved upon the drawbacks of rapeseed which was more suited for industrial use (Daun and Adolphe 1997). This new commodity with a trademarked Canadian Council of Canada licensed name (Statistics Canada 2009) responded to the demand for an edible oil with a meal component that was safe for large quantity utilization in livestock feed (Daun and Adolphe 1997). Over the years, refined analysis techniques, breeding improvements, the achievement of Generally Recognized as Safe (GRAS) status from the USDA, and scientific discussions around necessary limits and detrimental effects of glucosinolates

led to several alterations of the definition for canola (Daun and Adolphe 1997). While the consensus among various organizations is for the name to apply to varieties meeting specific levels of erucic acid and glucosinolates contents (COPA 2008; ISO 2013; CGC 2013b) and belonging to one of the two (*B. napus* or *B. rapa*) (CGC 2013a) or three *Brassica* species (*B. napus, B. rapa* or *B. juncea*) (COPA 2008; CCC 2013), the specific definition can vary slightly from source to source. A widely recognized standard Canadian definition is "seeds of the genus *Brassica* (*B. napus*, *B. rapa* or *B. juncea*) from which the oil shall contain less than 2% erucic acid in its fatty acid profile and the solid component shall contain less than 30 micromoles of any one or any mixture of 3-butenyl glucosinolate, 4-pentenyl glucosinolate, 2-hydroxy-3 butenyl glucosinolate, and 2-hydroxy- 4-pentenyl glucosinolate per gram of air-dry, oil-free solid" (Government of Canada 1983; CCC 2013).

The most valuable component of the canola seed is the oil (CCC 2013a), which makes up over 40% of the seed content (Daun 2006). Although producers are paid by total seed weight (and not oil content), the grade that they receive is affected by several factors, including distinctly green seeds (CGC 2013b), which has been shown to be directly related to chlorophyll content (Daun 2003). The CGC Official Grain Grading Guide for canola and rapeseed states that there is a limit of 2% distinctly green seed for canola, No.1 Canada, which receives a premium price above canola, No.2 Canada.

Canola customers are also concerned with several other measures of seed quality, including protein content, oleic, linoleic, linolenic acid, and total saturated fatty acid content, iodine value (a measure of unsaturation), and especially total oil content. The global customers for canola are seeking a high oil content (aiming for a 45% average content), and in many cases a meal component with a high protein, low

glucosinolates and low fibre content, which can be used in livestock feed. Customers focused on the oil component of the seed, or buying strictly the oil product generally prefer the oil to be low in glucosinolates, chlorophyll and total saturated fatty acids. More specifically, oil with a total saturated fatty acid content of 7% or less is preferred. There is some variation in the desired fatty acid profile specifications, but a large number of markets select canola oil for its nutritional qualities and heart-healthy properties, which (aside from low total saturated fatty acid component) include high mono- and polyunsaturated fatty acids and a source of omega-3 and omega-6 fatty acids (all due to the oleic, linoleic and linolenic acid components). Several customers also prefer oil higher in oleic acid, for its increased shelf-life, lack of *trans* fats, and being an omega-9 fatty acid. Of course, the health-concious markets for canola oil also prefer a very low erucic acid content, since the oil is primarily being utilized for human consumption (CCC 2011b; CCC 2011c; 2013b). However, specialty markets still exist for high-erucic acid rapeseed (HEAR) which use it for products such as industrial lubricants, plastics and detergents (Statistics Canada 2009). Canadian canola customers are also concerned with canola being a registered (as opposed to a de-registerd) variety, not containing any pesticide (including malathion) residues or animal protein (including blood and bone meal), and being free of any other sanitary or phytosanitary concerns (ex. presence of the blackleg fungus) (CCC 2011b; CCC 2011c; 2013b).

Canadian canola is grown in thousands of fields across a vast area where it is subject to a range of weather conditions that cannot be controlled. It is known that growing season weather affects the quality parameters for canola, which creates variability in the levels of several important components of canola quality year-by year (Canvin 1965; Daun 2006). Customers for canola prefer to know what they can

expect in terms of canola quality prior to the end of the growing season. This highlights a need for canola quality predictive models which can estimate the quality of the crop prior to harvest. Predictions of pre-harvest canola quality would improve the efficiency and logistics of sourcing and mixing canola for oil crushers, stimulate canola breeders' ability to create varieties adapted to certain weather stresses that are currently impacting canola quality, and allow worldwide customers to continue to purchase high quality Canadian canola with confidence.

The focus of this study was canola quality prediction based on the impacts of growing season weather at various stages of canola development. There were nine separate canola quality parameters investigated, including total glucosinolates, chlorophyll content, oleic, linoleic, linolenic acid and total saturated fatty acid content, iodine value, total oil content and protein content. Since erucic acid content is not currently a concern for canola customers, this parameter was not included in this study.

The recent increased number of weather stations in western Canada has reduced the distance from any given field to a source of weather data, which has improved the accuracy with which local weather conditions can be estimated at a canola sample site. The weather was quantified at each individual canola sampling site using both observed and calculated weather parameters from the nearest weather station, including minimum, maximum, average and range of temperatures, accumulated precipitation, various heat and cold stress measures, different evapotranspiration estimates and a water stress index (WSI) for various lengths of time related to crop development. The Physiological Day (P-Day) method of estimating canola phenology was considered more accurate than the Growing Degree Days (GDD) or calendar-day estimates of development (see Chapter two). Thus, P-

Days were utilized to determine canola growth stage at each individual sample site based on the seeding date and the daily maximum and minimum air temperature. This approach was used to help isolate the effects of weather during specific growth stages of canola.

The study objectives were:

a) To quantify the impact of environment, genotype and genotype by environment interaction on canola quality in western Canada
b) To construct models that could be used to predict the impact of growing season weather on canola quality in western Canada

3.3 Materials and Methods

3.3.1 Sample Collection and Variety Selection

The canola samples used in this study were from three different sources: the intensive field study sites (referred to as the 2009TDField dataset), collaborating companies' field trial sites (referred to as the 2009Field dataset), and the CGC Harvest Surveys in 2008 and 2009 (2008HS and 2009HS datasets). Since the Harvest Survey would provide the greatest number of samples and was the first available source of data, the variety selection was primarily based on the 2008 Harvest Survey data, keeping in mind that the selection should include standard varieties that could be used in field trials and the intensive field study. It was also essential that only canola, No. 1 Canada samples of low erucic acid and low glucosinolates *B. napus* varieties were considered for the study, in order to eliminate outliers (that could skew data) and the effects of producer management on canola samples as much as possible. However, it is understood that this strategy also reduced the full range of canola quality that could occur within a growing season as well as any quantification of the full effect of more

extreme weather conditions which could produce poor quality canola that would be graded as No. 2 or lower.

From the thousands of canola samples voluntarily submitted to the 2008 CGC Harvest Survey by producers across western Canada, 164 samples of the varieties 1841, 5020, 5030, 34-65, 71-45RR and SP Banner (Table 3.1) were selected for the study. The selection of varieties was based on several criteria, including an adequate number of samples which had their growing location and seeding date supplied on the sample package. The selection of varieties also considered the longevity, geographic distribution, distribution within quality parameters, and the popularity. All varieties utilized were within the top ten canola seeded acres in western Canada.

It was decided that both open pollinated (OP) (34-65 and SP Banner) and hybrid (1841, 5020, 5030 and 71-45RR) varieties should be used, despite fewer samples within open pollinated varieties, to provide phenotypic diversity. Two OP varieties (rather than one) were included to prevent conclusions about OP crops from being based on just one variety. Although SP Banner and SP Desirable had the highest number of samples per OP variety, SP Desirable was dropped in favor of 34-65 to increase genetic diversity. The genetics of SP Banner and SP Desirable were expected to be quite similar since both were from the Saskatchewan Wheat Pool breeding program. SP Banner had more samples available and they were spread across a wider geographic distribution than SP Desirable.

Varieties from various breeding programs were included, with 34-65 and 71-45RR from Monsanto, 5020 and 5030 from Bayer and the variety 1841 from Agriprogress. The hybrid variety, 5020 had the highest number of samples in the study and had been available, and fairly popular, since 2004, which is a relatively long time for a canola variety. There were many samples of both 5070 and 5030, but 5030

was expected to be the next popular variety from Bayer, while 5070 was soon going to be discontinued. Rounding out the group was variety 71-45RR, which, as a Round-Up Ready™ variety, would add further diversity to the group and was quite popular.

The varieties SP Banner, 71-45RR, and 34-65 had each been grown since 2006 and the 5020, 5030, and 1841 varieties had each been grown since 2004 (suggesting popularity amongst producers and relevance to the industry). All the varieties selected were distributed across western Canada, with each of the six varieties present in each of the three prairie provinces, excluding British Columbian samples which were only from a small region in the B.C. Peace (River) region. Most of the varieties had between 20% and 50% of their samples within each of the province. Preliminary statistics on the sample quality parameters for each of the selected varieties indicated that there was an adequate variation in quality for the purpose of this study but a fairly normal distribution within each quality parameter without any extreme outliers.

Table 3.1. Genotypes selected for the study.

Variety	Number of Samples*	Type: Hybrid or Open Pollinated (OP)	Company	Year of Commercial Availability
1841	11	Hybrid	Agriprogress	2004
5020	110	Hybrid	Bayer	2004
5030	43	Hybrid	Bayer	2004
34-65	15	OP	Monsanto	2006
71-45 RR	47	Hybrid	Monsanto	2006
SP Banner	21	OP	Viterra	2006

*These values include samples from all the individual datasets

After the varieties were selected, Canadian Grain Commission information, including seeding and swathing/harvesting dates, location and sample number was compiled and stored for later reference. It was also arranged for the intensive field study and additional field sites to include one of the six varieties at each field trial site to make up the 2009TDField and 2009Field datasets, respectively. Following the 2009 growing season, samples with required information (seeding and

swathing/harvesting dates, location and sample number) which belonged to one of the six varieties were selected for the 2009HS dataset.

3.3.2 Intensive Field Study

Seven field sites were used in 2009, each with meteorological instruments installed adjacent to the field or plot, and each growing one of the canola varieties utilized in this study (Table 3.2). The meteorological data collected included air temperature and relative humidity, wind speed, incoming solar radiation and precipitation. Frequent observations during the growing season facilitated the testing of canola phenology models and provided canola samples from which growing season weather conditions during specific growth stages were known.

3.3.3 Additional Field Sites

The samples provided from the fifteen additional field sites included in this study were obtained through collaboration with PioneerHybrid and Bayer. Weather stations located on or near these additional field sites were operated by the collaborating companies and the raw data (which included all necessary information for observed and calculated weather parameters) were provided along with the physical samples for compilation and analysis. A synopsis of these sites is provided in Table 3.3.

The source of samples was an important consideration during interpretation of the results because one source was only from Manitoba sites (2009TDField), some datasets were from sites associated with collaborating companies (2009Field and 2009TDField) and other sites were only from producers (2008HS and 2009HS).

Table 3.2. Intensive field study site summary.

Location	Variety	Collab-orating Company	Legal Land Location	Long (N)	Lat (W)	Weather Equipment
Balmoral	5020	Bayer	SE 31-04-05-1W	49.34	98.12	WatchDog station
Carman	5020	Pioneer-Hybrid	NE 01-08-10-1W	49.66	98.58	Data logging Rain Gauges
Jordan Corner	5020	Monsanto	NE- 28-14-02 E1	50.22	97.26	WatchDog station
Oakville	71-45 RR	Monsanto	SE 21-06-04-1W	49.49	97.94	Campbell Scientific weather station
Portage	5020	Bayer	NW 11-12-8-1W	50.00	98.46	Campbell Scientific weather station
Rathwell	5020	Pioneer-Hybrid	NE 13-11-05-1W	49.93	98.01	Data logging Rain Gauges
Rosebank	5020	Pioneer-Hybrid	SE 26-4-5-1W	49.34	98.03	Data logging Rain Gauges

The 2008HS and 2009HS datasets contained samples from the 2008 and the 2009 CGC Harvest Surveys, respectively, while the 2008&2009HS dataset contained the combined samples from both the 2008HS and 2009HS datasets. Data from the 2009Field dataset contained samples that were collected by collaborators at PioneerHybrid and Bayer from their field trials across western Canada. Data from the 2009TDField dataset were collected across Manitoba from individual field or large-scale plot collaborative sites with Bayer, Monsanto, or PioneerHybrid. The 2009AllField dataset included a combination of samples in the 2009Field and 2009TDField datasets, while the 2009All dataset included samples from the 2009HS, 2009Field and 2009TDField datasets and the All2008&2009 dataset included all samples from all the datasets. Some raw weather data were also provided by collaborating companies which had weather stations at or near the field sites.

Table 3.3 Additional field site summary.

Sample ID	Location	Variety	Co-operating Company	Legal Land Location	Longitude (Decimal Degrees)	Latitude (Decimal Degrees)
084927_5020	Calmar, AB	5020	PioneerHybrid	SE 08-49-27	-113.909	53.20949
245125_5020	Edmonton, AB	5020	PioneerHybrid	24-51-25	-113.56	53.41424
275720_5020	Redwater, AB	5020	PioneerHybrid	27-57-20	-112.883	53.95242
293926_5020	LaCombe, AB	5020	PioneerHybrid	29-39-26	-113.707	52.38653
2ELY	Elfros, SK	5020	PioneerHybrid	NE 32-32-14 2W	-103.949	51.79109
2MKY	Meskanaw, SK	5020	PioneerHybrid	SE 13-44-22 2W	-105.058	52.7882
2RDY	Radisson, SK	5020	PioneerHybrid	SW 16-40-10 3W	-107.39	52.43831
2SKY	Saskatoon, SK	5020	PioneerHybrid	SW 21-37-4 3W	-106.522	52.1912
2WTY	Watrous, SK	5020	PioneerHybrid	NW 8-31-24 2W	-105.376	51.64596
303526_5020	Innisfail, AB	5020	PioneerHybrid	30-35-26	-113.715	52.03821
306125_5020	Westlock, AB	5020	PioneerHybrid	30-61-25	-113.744	54.30074
335025_5020	Leduc, AB	5020	PioneerHybrid	33-50-25	-113.593	53.36238
3NPY	Neepawa, MB	5020	PioneerHybrid	33-14-15 1W	-99.4656	50.23383
P102_5030	Portage, MB	5030	Bayer	SE 31-04-05 1W	-99.4674	50.23333
SW102_5030	Balmoral, MB	5030	Bayer	NE 01-08-10 1W	-98.6993	49.62702

While there were several different sources of all the physical samples (Table 3.4), the same quality analysis was carried out with all samples and the same method of compiling weather data was followed for all samples. Each dataset was analyzed for differences in canola quality to determine the impact of each sample source.

Table 3.4. Canola sample datasets.

Dataset	Description of the samples that each dataset contains
2008HS	164 canola samples retrieved from the 2008 CGC Harvest Survey
2009HS	61 canola samples retrieved from the 2009 CGC Harvest Survey
2008&2009HS	225 of the canola samples in both the 2008HS and 2009HS datasets
2009Field	15 canola samples from 2009 field trials across western Canada
2009TDField	7 canola samples from various field sites across Manitoba in 2009
2009AllField	22 canola samples from both the 2009Field and 2009TDField datasets
2009All	83 canola samples from 2009HS, 2009Field and 2009TDField datasets
All2008&2009	247 canola samples from 2008HS, 2009HS, 2009Field and 2009TDField datasets

3.3.4 Weather Analysis

Daily weather data were compiled from three separate data sources. Weather data corresponding to canola samples from the intensive field study were downloaded directly from the Campbell Scientific and WatchDog weather stations installed at each site. The Campbell Scientific weather stations measured air temperature and relative humidity with a radiation shielded probe (CS 500, Campbell Sci., Logan, Utah) at a height of 1.75 m and they were set up on level ground at the edge of the field, according to specifications given by the Campbell Scientific manuals (Campbell Scientific, Inc. 2013). The Campbell Scientific CR1000 dataloggers logged measurements for each sensor every 10 seconds to produce both hourly and daily averages, and accumulated totals for precipitation. The WatchDog weather stations (model 900ET) included a radiation shielded temperature and relative humidity sensor (Spectrum Technologies Inc., Aurora, IL). Instantaneous readings were logged every 10 minutes.

Weather data corresponding to canola samples from the additional field sites were primarily from WatchDog weather stations using a SpecWare 8 Pro program and tipping buckets, with gap filling from nearby Environment Canada or (the former Canadian Wheat Board's) WeatherFarm stations. Weather data corresponding to canola samples from the 2008 and 2009 Harvest Survey samples was taken from the closest Environment Canada network or WeatherFarm network weather station.

Daily weather data from the seeding date until the swathing or (straight-cut) harvesting date were compiled for each canola sample and used to create a comprehensive description of the weather conditions at each sample location. These were then used to quantify the heat, cold, precipitation and related stresses on the

canola crops. Some of the weather parameters were based directly on observations and others were calculated values using a variety of estimation techniques (Table 3.6).

Weather parameters can be divided into observed weather data, potential temperature stress, and estimated water usage and stress. In all cases, the values were determined for each day, from seeding until swathing/harvest at each of the 247 sites. These values were later calculated for each of the six phenological stages (3.2, 4.2, 4.3, 4.4, 5.2, and 5.4), the five cumulative parameters (ex. seeding through 4.2, 4.3, 4.4, 5.2, or 5.4), and the ten combinations of two or more consecutive stages (ex. 4.2 through 5.4) (Table 3.5 and Table 3.7). Then all the total daily precipitation values, daily maximum, minimum, mean and range of temperatures were averaged across all days included in the duration identified, for each sample (Table 3.6).

3.3.4.1 Observed Weather Data. The daily maximum (MaxT), minimum (MinT), average (AveT) and range of air temperature (RangeT) as well as total daily precipitation (SumPrecip) were determined for each day. At the intensive field sites (excluding the periods which were filled in with nearby weather stations) the highest and lowest hourly values each day were selected for maximum and minimum daily temperature and used to calculate the air temperature range (maximum - minimum temperature) for each day. A mean of all the hourly temperature values within each day was used to determine the average temperature. Daily precipitation values were the resulting summation of all hourly precipitation values. For weather stations that only provided maximum and minimum daily temperatures, the average was calculated by finding the mean of these numbers and the range by determining the difference between them. Daily precipitation values were used as given.

Table 3.5 Phenological stages used to aggregate the weather parameters.

Pheno-logical Stage	Description†	Alternative Name Used in Predictive Models
3.2	Bud Stage: Flower cluster raised above level of rosette	A (ex. A_SDD>19)
4.2	Flower Stage: Many flowers opened, lower pods elongating	B (ex. B_CD<8)
4.3	Flower Stage: Lower pods starting to fill	C (ex. C_EToSum)
4.4	Flower Stage: Flowering complete, seed enlarging in lower pods	D (ex. D_SDD>31)
5.2	Ripening Stage: Seeds in lower pods green	E (ex. E_CDD<11)
5.4	Ripening Stage: Seeds in lower pods yellow or brown	F (ex. F_SD>28)

†Source of descriptions of phenological stages: Canola Council of Canada (2011a).

3.3.4.2 Potential Temperature Stress. Potential heat and cold stress were broken into stress degree days and stress days. Stress degree days (SDD for heat stress and CDD for cold stress) focus on the intensity of temperature stress by measuring the accumulation of temperature units above or below various thresholds. Stress Days (SD for heat stress and CD for cold stress) focus on the duration of temperature stress by measuring the number of days with a temperature above or below various thresholds throughout each phenological stage(s) identified. The threshold temperatures for the cold stress calculations ($Tbase_C$) were 5^oC, 8^oC, 11^oC, 14^oC, and 17^oC. The threshold temperatures for the heat stress calculations ($Tbase_H$) were 19^oC, 22^oC, 25^oC, 28^oC, 31^oC and 34^oC. However, if the minimum temperature (MinT) was not below $Tbase_C$ for a given day, or the maximum temperature (MaxT) did not exceed $Tbase_H$ for a given day, the stress degree day value for the day was set at zero (see below).

Heat stress equations:

If $\sum MaxT > Tbase_H$

$SD=1$

$SDD = \sum (MaxT - Tbase_H)$

where:
MaxT was the daily maximum temperature for the phenological stage(s) identified
$Tbase_H$ was equal to 19°C, 22°C, 25°C, 28°C, 31°C or 34°C

Cold stress equations:

If $\sum MinT < Tbase_C$

$CD=1$

$CDD = \sum (Tbase_C - MinT)$

where:
MinT was the daily minimum temperature for the phenological stage(s) identified
$Tbase_C$ was equal to 5°C, 8°C, 11°C, 14°C, or 17°C

3.3.4.3 Estimated Water Usage and Stress. Estimated water usage and stress were characterized by reference evapotranspiration (ETo), crop specific evapotranspiration (ETc) and the water stress index (WSI). Evapotranspiration was characterized using an average (EToAve and ETcAve) by finding the mean of all the daily Eto or ETc values throughout the phenological stage(s) identified (for each sample) and as a summation (EToSum and ETcSum) by finding the total of all daily Eto or ETc values throughout the phenological stage(s) identified, for each sample.

The reference evapotranspiration (ETo) was determined using the method of Hargreaves et al. (1985).

ETo = 0.0022 x RA x (TC + 17.8) x TD^0.5

where:
RA = 0.408* R_a

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)]$$

R_a extraterrestrial radiation, MJ m^{-2} day^{-1}
G_{sc} solar constant = 0.0820 MJ m^{-2} min^{-1}
d_r =inverse relative distance Earth-Sun
w_s =sunset hour angle [rad]
j =latitude [rad]
d =solar decimation [rad].

TC = average daily temperature
TD = daily range in temperature

Evaporative demand was also characterized by crop evapotranspiration (ETc), which is based on the reference evapotranspiration values, but adjusted to the requirements of a canola crop (ETo multiplied by a crop coefficient, Kc), which described the crop moisture needs at each phenological stage of development. Since there were no published Kc values available for each of the growth stages investigated in this study, they were created using base values from the FAO (Allen et al. 1998) and input from several other credible sources (Agrimet 1994; Thomas 1995; Van der Gulik and Nyvall 2001; ICMS 2004; AARD 2009), along with a basic understanding of canola growth and development (Thomas 1995; AARD 2009). Once values were set for each of the growth stages (including the six stages used in this study), they were plotted out on a graph, and the equation for the lines connecting the successive stages was recorded. These equations and their corresponding growth stages, which were determined from their corresponding P-Day thresholds, were used in the study and are shown below. The full description of the development of the Kc values used in this study is provided in Appendix 1.

The P Day relationships to Kc values are given below:

If 0 < P-Day > 54.5	Kc = 0.2
If 54.5 < P-Day > 139.7	Kc = 0.0018x+0.104
If 139.7 < P-Day > 297.86	Kc = 0.0032x-.0916
If 297.86 < P-Day > 405.38	Kc = 0.0021x+.2267
If 405.38 < P-Day > 478.88	Kc = 0.0010x+.6613
If 478.88 < P-Day > 601.14	Kc = -0.0008x+1.5417
If 601.14 < P-Day > 734.89	Kc = -0.0019x+2.1736
If 734.89 < P-Day > 814.68	Kc = -0.0025x+2.6421

where x = P-Days

A daily WSI was also calculated. This value is a measure of crop stress based on moisture supply (total daily precipitation) versus moisture demand (total daily crop

evapotranspiration). This is simply determined by subtracting the daily ETc from total daily precipitation. This daily value is then accumulated over the course of the phenological stage(s) of interest.

$$WSI = \sum (\text{Daily precipitation} - \text{daily Etc})$$

For many canola samples, the WSI values calculated over certain phenological growth stages (especially the cumulative ones, including stages later in development) produced negative values. This is normal in the western Canadian prairies where cumulative evapotranspiration generally surpasses total precipitation as the growing season progresses (AAFC 2010; MAFRI 2013a). However, the negative values did pose a challenge to the statistical analysis (partial least squares analysis) that would be carried out (the program can not deal with negative values), so 400 was added to all the WSI values in the dataset and henceforward referred to as WSI_t, or WSI transformed.

$$WSI_t = WSI + 400$$

A summary of the daily weather parameters observed and calculated for this study are displayed in Table 3.6 A summary of the phenological growth stages over which the weather parameters were accumulated is given in Table 3.7. The total of 32 different weather parameters determined over 21 different combinations of phenological growth phases produced a total of 672 independent variables for assessment of canola quality.

The development stages of canola in the Intensive Field Study were observed directly. For the Harvest Survey samples, canola phenological development was modeled using seeding date and the P-Day method described in chapter two. Each of the weather parameters was compiled for every canola sample location, and for each stage of development.

An average of the mean daily temperatures for all 247 samples from seeding date until the end of stage 4.4 (cumulative) was calculated (14.95^{o}C). Samples from sites with mean daily temperatures less than or equal to the mean were categorized as "cool temperature sites" and samples from sites with mean daily temperatures above were were categorized as "warm temperature sites". In total, there were 120 cool temperature sites and 127 warm temperature sites (which were considered to be fairly equal samples sizes).

An average of the cumulative precipitation for all 247 samples from seeding date until the end of stage 4.4 (cumulative) was calculated (152.84 cm). Samples from sites with growing season precipitation less than or equal to the mean were categorized as "low precipitation sites" and samples from sites with growing season precipitation greater than the mean were categorized as "high precipitation sites". In total, there were 132 low precipitation sites and 115 high precipitation sites.

The mean daily temperature and cumulative precipitation to stage 4.4 were selected because this was the longest possible timeframe that best represented the growing season with a minimum of missing values.

Table 3.6. Basic weather parameter descriptions and method of calculation.

Independent Variable	Variable Description
MaxT	Average of all Daily Maximum Temperatures for a defined physiological stage
MinT	Average of all Minimum Daily Temperatures for a defined physiological stage
SumPrecip	Accumulation of all Daily Precipitation for a defined physiological stage
AveT	Average of all Daily Mean* Temperatures for a defined physiological stage
RangeT	Average of all Daily Temperature Ranges† for a defined physiological stage
SDD>19	Total Heat Stress Degree Days above 19^{o}C for a defined physiological stage
SD>19	Total Heat Stress Days above 19^{o}C for a defined physiological stage
SDD>22	Total Heat Stress Degree Days above 22^{o}C for a defined physiological stage
SD>22	Total Heat Stress Days above 22^{o}C for a defined physiological stage
SDD>25	Total Heat Stress Degree Days above 25^{o}C for a defined physiological stage
SD>25	Total Heat Stress Days above 25^{o}C for a defined physiological stage
SDD>28	Total Heat Stress Degree Days above 28^{o}C for a defined physiological stage
SD>28	Total Heat Stress Days above 28^{o}C for a defined physiological stage
SDD>31	Total Heat Stress Degree Days above 31^{o}C for a defined physiological stage
SD>31	Total Heat Stress Days above 31^{o}C for a defined physiological stage
SDD>34	Total Heat Stress Degree Days above 34^{o}C for a defined physiological stage
SD>34	Total Heat Stress Days above 34^{o}C for a defined physiological stage

Table 3.6. Continued.

Table 3.6. Continued.

Independent Variable	
EToSum	Total daily ETo accumulated from one defined physiological stage until the end of another defined physiological stage
EToAve	Daily ETo averaged from one defined physiological stage until the end of another defined physiological stage
ETcSum	Total daily ETc accumulated from one defined physiological stage until the end of another defined physiological stage
ETcAve	Daily ETc averaged from one defined physiological stage until the end of another defined physiological stage
WSI_tSum	Total WSI_t calculated from one defined physiological stage until the end of the defined physiological stage
CDD<5	Total Cold Stress Degree Days below 5^oC for a defined physiological stage
CD<5	Total Cold Stress Days below 5^oC for a defined physiological stage
CDD<8	Total Cold Stress Degree Days below 8^oC for a defined physiological stage
CD<8	Total Cold Stress Days below 8^oC for a defined physiological stage
CDD<11	Total Cold Stress Degree Days below 11^oC for a defined physiological stage
CD<11	Total Cold Stress Days below 11^oC for a defined physiological stage
CDD<14	Total Cold Stress Degree Days below 14^oC for a defined physiological stage
CD<14	Total Cold Stress Days below 14^oC for a defined physiological stage
CDD<17	Total Cold Stress Degree Days below 17^oC for a defined physiological stage
CD<17	Total Cold Stress Days below 17^oC for a defined physiological stage
MaxTCum	Average of all Daily Maximum Temperatures from seeding until the end of the defined physiological stage
MinTCum	Average of all Minimum Daily Temperatures from seeding until the end of the defined physiological stage
SumPrecipCum	Accumulation of all Daily Precipitation from seeding until the end of the defined physiological stage
AveTCum	Average of all Daily Mean* Temperatures from seeding until the end of the defined physiological stage
RangeTCum	Average of all Daily Temperature Ranges† from seeding until the end of the defined physiological stage
SDD>19Cum	Total Heat Stress Degree Days above 19^oC from seeding until the end of the defined physiological stage
SD>19Cum	Total Heat Stress Days above 19^oC from seeding until the end of the defined physiological stage
SDD>22Cum	Total Heat Stress Degree Days above 22^oC from seeding until the end of the defined physiological stage
SD>22Cum	Total Heat Stress Days above 22^oC from seeding until the end of the defined physiological stage
SDD>25Cum	Total Heat Stress Degree Days above 25^oC from seeding until the end of the defined physiological stage
SD>25Cum	Total Heat Stress Days above 25^oC from seeding until the end of the defined physiological stage
SDD>28Cum	Total Heat Stress Degree Days above 28^oC from seeding until the end of the defined physiological stage
SD>28Cum	Total Heat Stress Days above 28^oC from seeding until the end of the defined physiological stage
SDD>31Cum	Total Heat Stress Degree Days above 31^oC from seeding until the end of the defined physiological stage
SD>31Cum	Total Heat Stress Days above 31^oC from seeding until the end of the defined physiological stage
SDD>34Cum	Total Heat Stress Degree Days above 34^oC from seeding until the end of the defined physiological stage
SD>34Cum	Total Heat Stress Days above 34^oC from seeding until the end of the defined physiological stage
EToSumCum	Total daily ETo accumulated from seeding until the end of another defined physiological stage

EToAveCum	Daily ETo averaged from seeding until the end of another defined physiological stage
ETcSumCum	Total daily ETc accumulated from seeding until the end of another defined physiological stage
ETcAveCum	Daily ETc averaged from seeding until the end of another defined physiological stage
WSI_tSumCum	Total WSI_t calculated from seeding until the end of the defined physiological stage

*Calculated from averaging the daily maximum and daily minimum temperatures
†Calculated as the difference between daily maximum and daily minimum temperatures

Table 3.7. Phenological growth stages over which the weather variables were calculated.

Data subset	Examples
Each of the 6 phenological stages	3.2, 4.2, 4.3, 4.4, 5.2, 5.4
Each of the 5 cumulative stages	Seeding through stage 4.2 Seeding through stage 4.3 Seeding through stage 4.4 Seeding through stage 5.2 Seeding through stage 5.4
Each of the 10 sequential combinations of phenological stages (excluding 'Seeding through stage 4.2', which was already addressed)	Stage 4.2 through stage 4.3 Stage 4.2 through stage 4.4 Stage 4.2 through stage 5.2 Stage 4.2 through stage 5.4 Stage 4.3 through stage 4.4 Stage 4.3 through stage 5.2 Stage 4.3 through stage 5.4 Stage 4.4 through stage 5.2 Stage 4.4 through stage 5.4 Stage 5.2 through stage 5.4

3.3.5 Canola Quality Analysis

Canola quality analyses were conducted at the CGC's Grain Research Laboratory in Winnipeg according to methods created by the International Organization for Standardization or the America Oil Chemists' Society (CGC 2010). The methods and details of analysis for each quality parameter are summarized in Table 3.8. There was one canola sample which could not be obtained from a collaborating industry partner due to confidentiality regulations. However, quality information on the sample was provided by the company along with the assurance that it was obtained by methods equivalent to those used in the CGC's Grain Research Laboratory.

When reporting quality parameters, oil and protein content were reported on an 8.5% moisture basis, total saturated fatty acids were the sum of palmitic (C16:0), stearic (C18:0), arachidic (C20:0), behenic (C22:0), and lignoceric (C24:0), and fatty acids were reported as a percentage of total fatty acids rather than percentage of total seed, which would produce much lower values than those reported in the current study or other studies (Stefansson and Storgaard 1969).

The three methods of analysis carried out on the canola samples were Fatty Acid Methyl Esters (FAMEs), Near Infrared (NIR) and Nuclear Magnetic Resonance (NMR) spectroscopy. The data from the method of analysis which was most suitable (produced the data with the highest degree of accuracy) for each quality parameter was utilized in the quality dataset. Therefore, although the NIR analysis yielded oil, protein, glucosinolates, chlorophyll, oleic acid, linolenic acid, total saturated fatty acids content and iodine values, only the protein, glucosinolates, and chlorophyll values were retained for the quality dataset. NMR analysis was the most appropriate analysis for providing the most accurate oil content values, and the oleic acid, linoleic acid, linolenic acid, total saturated fatty acids and iodine value were all provided from the FAMEs analysis results (since the FAMEs test is more specialized for fatty acid analysis than the NIR analysis).

3.3.5.1 NIR Analysis. Using the WinISI™ II program, whole seed analysis was conducted for each of the 247 canola samples. The outer glass of the sample cup was cleaned with Kimwipes®, then filled to the appropriate height with canola sample and gently placed in the machine without touching the glass. Both low and high canola sample standards (cv.46P50) confirmed the machine calibration accuracy by determining quality parameters were within the acceptable ranges.

3.3.5.2 NMR Analysis. The NMR analysis was completed using a Bruker NMS 110 Minispec to obtain oil content values for the canola samples. Each sample was analysed in quadruplet, with each replicate being removed without replacement to prevent any portion of the same sample from being measured twice and weighing approximately 25 grams. Four replicates of the standard sample (cv. 46A65) were run at the beginning of each sampling batch and duplicate replicates were run every five samples after that. Their values confirmed the accuracy and precision of the machine's measurements. The samples and the cylinder used for measuring the samples were all kept at approximately the same temperature to produce the most accurate results possible and the exterior of the cylinder was cleaned before each batch with Kimwipes®.

3.3.5.3 FAMEs Analysis. Canola samples were ground and prepared according to a wet lab standard operating procedure before being analyzed in an Agilent Automated Liquid Gas Chromatography Sampler to determine the fatty acid profile. Duplicate 10 gram sub-samples from each canola sample bag were ground up with the CGC grinder and placed into cone-shaped filter sheets resting over cylindrical beakers. Petroleum ether was poured over the ground up samples and allowed to drain through and excess moisture to evaporate overnight (in order to extract the oil).

The following day duplicate 50 uL oil samples were prepared for gas chromatography (GC) by means of a methyl-ester preparation method (which separates out the fatty acids from the rest of the molecules in the sample). This included adding 5 mL of iso-octane to each sample to dissolve the oil, mixing it for 15 seconds (with a vortex type mixer), then adding 500 uL 0.5M sodium methoxide to allow trans esterification, transforming the fatty acids engaged into a triglycerol molecule to be transformed into fatty acid methyl esters. The sample was then mixed

again for 15 to 20 seconds and left to stand for 30 minutes with a stopper cap on top. Next, 2 drops of 0.1% bromothymol blue indicator was added to the cocktail, followed by 300 uL of 1N hydrochloric acid to neutralize the basic solution and stop the reaction. Following this, 1 mL of 1.5% sodium carbonate was added to each sample, it was mixed for 15 to 20 seconds and topped up with approximately 5 mL of de-ionized water to finish washing the organic phase, then capped and left to stand for an hour. Finally, the fatty acid portion of the cocktail was pipetted into labelled vials, which were capped (with an automatic capper) and placed in the gas chromatography auto injector.

The samples were placed in the sequence: 46A65 (the standard check), high oleic acid check, three more 46A65 standard checks, twenty samples, three more 46A65 standard checks, followed by fifteen samples and three more 46A65 standard checks following each additional fifteen samples.

Table 3.8. Summary of the canola quality parameters analyzed for this study.

Dependent variable	Method of Analysis	Details
Oil content[a], %	NMR[d]	The approximate amount of lipid material that can be extracted from crushing canola seed
Protein content[b],%	NIR[d]	An estimation of the nitrogen content in the seed
Chlorophyll content, mg/kg in seed	NIR[d]	A green pigment found in immature seeds which is undesirable for oil processing
Total glucosinolates[a], µmol/g	NIR[d]	Natural toxicants that cause a bad odor and can be detrimental to livestock in large quantities
Oleic acid, % in oil	FAME[e]	Mono-unsaturated fatty acid which are comprised of 18 carbons and have 1 double bond; C18:1
Linoleic acid, % in oil	FAME[e]	Poly-unsaturated fatty acid which are comprised of 18 carbons and have 2 double bonds; C18:2
Linolenic acid, % in oil	FAME[e]	Poly-unsaturated fatty acid which are comprised of 18 carbons and have 3 double bonds; C18:3
Total saturated fatty acids[c], % in oil	FAME[e]	Saturated fatty acids which have no double bonds and are undesirable from a health prospective
Iodine value	FAME[e]	A measure of unsaturation, which is the amount of iodine that will combine with 100g of oil

[a]8.5% moisture basis
[b]N x 6.25, 8.5% moisture basis

[c]Total saturated fatty acids are the sum of palmitic (C16:0), stearic (C18:0), arachidic (C20:0), behenic (C22:0), and lignoceric (C24:0)
[d]Nuclear Magnetic Resonance Spectroscopy
[e]Fatty Acid Methyl Esters analysis
(Barthet 2009; CGC 2010)

3.3.6 Statistical Analysis

All canola quality parameters were analyzed with the UNIVARIATE procedure from SAS (SAS Institute 2005) to test for normality. The basic statistical measures as well as the P-value and W statistic from the Shapiro-Wilk's test are presented in Table 3.9. A quality parameter was considered to have a normal distribution if $P \geq 0.05$ and/or $W > 0.90$, which was true for all quality parameters.

Table 3.9. Canola quality parameter tests for normality.

Basic Statistical Measures	Oil %	Protein %	Chloro %	Glucos %	Oleic acid %	Linoleic acid %	Linolenic acid %	Sats %	Iodine Value
Mean	45.09	20.14	10.92	8.61	62.73	18.74	9.47	7.02	112.62
Std Deviation	2.00	1.96	5.37	1.54	1.60	1.17	1.02	0.35	2.11
Skewness	-0.16	0.06	0.27	0.51	-0.50	0.49	0.54	-0.37	0.49
Kurtosis	-0.57	-0.38	-0.08	0.40	0.35	0.46	0.46	0.43	0.08
Shapiro-Wilk's Test									
W Statistic	0.990	0.995	0.989	0.977	0.980	0.984	0.981	0.984	0.983
Pr< W	0.077	0.533	0.070	0.001	0.002	0.008	0.002	0.008	0.004
N	246	246	246	246	247	247	247	247	246

Key: Chloro= Chlorophyll, Glucos= Glucosinolates, Sats= Total Saturated Fatty Acids

There was no typical experimental design for this study (because part of the uniqueness of the study is that it accurately reflects the growing conditions of canola crops across western Canada). Canola samples were not replicated at any locations, and each sample was sourced from a different location with a unique set of management and environmental conditions, including soil type, soil fertility, topography, drainage, and tillage practices, among others. There was a large sample size (n=247) of canola crops randomly distributed across western Canada. Individual sites acted as pseudo replicates for each of the data subsets that were tested (e.g. by latitude). The distribution of samples across provinces, soil zones and climates is

expected to result in an even distribution of environmental and management effects across all the samples. The selection of only canola, No. 1 Canada samples for the study should have prevented any samples grown under poor conditions from being included. Therefore, it is assumed that no extreme negative management or environmental conditions would have affected the samples. Conversely, it is also assumed that achieving canola, No. 1 Canada means the crops received adequate nutrients amongst other basic management-influenced factors (ex. seeding rates, depth, etc.).

The data were grouped into subsets by data source, variety, type (OP or hybrid), germplasm (Roundup-Ready or Liberty Link), latitude (between 49^{o} and equal to or north of 54^{o}), warm or cool mean daily temperatures and high or low cumulative precipitation. Each data subset was analyzed for differences between means using PROC MIXED and the LSMEANS statement adjusted with the Tukey-Kramer test (with PDIFF option) in SAS 9.2 (SAS 2005). The PROC MIXED program was used to accommodate the unequal variances between subsets. The Tukey-Kramer test is a moderately conservative test which becomes increasingly conservative for more unbalanced data and therefore a good fit for the data in this study (Cardinal and Aitken 2006). The default settings of Restricted Maximum Likeliness (REML) and estimation method and Type III analysis were used in the program. Type III analysis was used because it is best suited for unbalanced data, and ensures that the order of effects does not change if the model is run in different ways (Crow 2009).

3.3.6.1 Statistics Correction. When reviewing the results from the least squared means (LSM) tests in Tables 3.10 through 3.14, extra caution must be taken. While the use of the Tukey-Kramer method was the most appropriate test to determine the

difference between means of each of the varieties, datasets, latitudes, types, temperatures, precipitation and germplasm data subsets, the outputs it produced had their shortcomings. Some of the standard error values produced for individual subsets (ex. for one variety) were fairly high (> 0.3) and the standard errors across the subsets of any one factor (ex. varieties) were quite variable. Some of this variability in standard errors stems from the unbalanced nature of the data, therefore conclusions drawn from the statistical analysis of canola quality are considered suggested conclusions rather than absolute conclusions.

3.3.7 Model Development

The Partial Least Squares (PLS) method was used to create a predictive model that quantified the effect of weather variables (measured over various stage(s) of canola development) on each of the canola quality variables. Although multiple linear regression (Finlay et al. 2007) and multivariate regression analysis (Jarvis et al. 2008) are more commonly utilized in agriculture, the nature of the data in this study is a better fit for the PLS method because (i) it can be used with a large number of explanatory variables, even when these exceed the number of observations, (ii) it can run when there is missing data, and (iii) it can handle explanatory variables with a high degree of collinearity (Tobias 1995). This study utilized 672 weather parameters as explanatory variables for quality parameters of each of 247 canola samples, many of which were likely to have a high degree of collinearity, and included missing data (for weather parameters specific to phenological stages which were not reached).

The goal was to determine predictive models that had the fewest predictors, whose Root Mean predicted residual sum of squares (PRESS) statistic was as low as possible, and explained the maximum amount of variation in response variables. The predictors (independent variables) were the 672 observed and calculated weather

variables for each of the 247 canola samples. The responses (dependent variables) were the nine canola quality parameters (oil, protein, chlorophyll, glucosinolates, oleic acid, linoleic acid, linolenic acid, total saturated fatty acids and iodine value) determined for each of the 247 canola samples. This statistical analysis resulted in the development of nine predictive models, one for each of the canola quality parameters.

A one-at-a-time cross-validation was run on each PLS model (SAS Institute Inc. 2013b). With this method 247 observations were read and 115 or 116 observations were used. The discrepancy (difference) between the number of observations read (the number of samples that the model acknowledges, but not necessarily uses) and the number of observations used (the number of samples that contribute to the construction of the model) was a result of some missing data in independent parameter values and one dependent parameter value (causing the model to not use the samples that had a missing data point). Many of the missing values for those weather parameters measured across a phenological growth stage late in development (ex. stage 5.4) by which time many crops had been swathed or harvested (although most crops that were straight-cut were often left standing in the field longer than those that were swathed). Naturally, the crops that did not complete phenological stage 5.4 could not produce a weather parameter value. For example, any sample cut or harvested before the crop reached the end of stage 5.4 had missing values for weather parameters measured over phenological stage 5.4 (independently or cumulatively).

Since each of the nine quality parameters determined that at least one of the weather parameters measured across phenological stage 5.4 had a high variable importance for the prediction (VIP) value, all the parameters measured over phenological stage 5.4 were left in the model. Unfortunately this caused the number

of variables which were read to decrease from 247 to 115 or 116 because the parameters which were measured over phenological stage 5.4 had 131 missing values. If the nine predictive models had not selected any of the parameters measured over phenological stage 5.4, all variables measured over this phenological stage could have been eliminated from the set of predictor variables and the number of observations used would have been higher.

In addition to missing values, PLS analysis can also run with datasets that contain zero values in the predictor variables (not in the response variables). This characteristic was beneficial, because there were some predictor variables which had zero values in this dataset. The zero values were generally in predictor variables which were quantifying heat or cold stress days or stress degree days (for more extreme temperature thresholds), that were not surpassed at every stage of development (such as the below 5^{o}C threshold or above 31^{o}C threshold).

In both cases, the ability of the PLS program to run with datasets that have some zero and missing values had proved beneficial. However, some of the predictor variables in this study had so many missing and zero values combined (out of the total number of observations) that the actual sample sizes of non-zero observations were quite small. This was a concern because the low number of non-zero observations left could provide an inaccurate representation (of a larger sample-sized version) of the predictor variable. This was the concern with predictor variables like heat stress days, heat stress degree days, cold (stress) days, and cold (stress) degree days. In an effort to prevent any variables with too few non-zero values from being run in the predictive models and potentially producing unreliable results, an exclusion threshold (as a percentage) was enforced. The value used for the threshold had to balance between incorporating as many weather parameters in the analysis as possible, while

eliminating all the weather parameters that would be problematic to the analysis. In order to prevent deleting potentially useful predictor variables, the threshold was set at a fairly conservative level (deleting as few predictor variables as possible).

It was decided that a good compromise between these considerations was, predictor variables (independent weather variables) with greater than 80% missing and zero-valued observations were eliminated. This percentage was used because there were 247 samples in the dataset, and if 200 of them had zero or missing values (200/247) this value would represent 80.97% of the samples. If the elimination threshold had been much higher (allowing more variables to have zero or missing variables and fewer non-zero or missing variables to represent a predictor variable), all the canola varieties in the study would likely not be included (which reduces the strength of the results). Conversely, while 48 or more non-zero, non-missing samples representing a predictor variable is much less than 247 total samples, it is still a relatively large number that can be expected to produce useful outcomes. Since the value 80.97% is more difficult to work with, it was rounded off to 80%, for ease of measurement.

Furthermore, the 80% threshold worked well with the dataset because it fell between natural groupings of (204-240) missing or zero-valued observations amongst the predictor variables. When the dataset was considered, there were a significant number of predictor variables with 204-240 missing and zero-valued observations, then another large group of predictor variables with 154-173 missing and zero-valued observations, followed by 131, 55-88, or 26-34 missing or zero-valued observations. (Many of the predictor variables measuring heat stress days and heat stress degree days at high thresholds across early phenological stages had between 204 and 240 zero-valued observations). Therefore, the 80% threshold eliminated all those

predictor variables with 204-240 missing or zero-valued observations while maximizing the number of observations that would be read and used.

This rule of elimination was followed regardless of the VIP value (a measure of how integral the variables are to the model) (SAS 2012), since the VIP values produced may have been improperly based on very few values. Enforcing this threshold on the initial dataset reduced the number of independent (predictor) variables in the model from 672 to 624.

The PLS program for each of the nine quality parameter models was determined through a typical process, as described in SAS Institute Inc. (2013b). A VIP value of 0.8 is often used as a threshold for elimination (Wold 1995), so it was initially used for this study. In this study, a higher VIP threshold was selected by incrementally increasing the VIP threshold by 0.1 for each run of the models as long as the percentage of variation in response variables accounted for did not significantly decrease. This was repeated until a new threshold was reached for each of the quality parameter models (because the predicting power of the model significantly dropped when the threshold was raised above this value), which dramatically cut down the size (number of predictors) of the predictive models. The elimination of numerous predictor variables was acceptable because this did not result in the percentage of variation in response variables accounted for to significantly decrease, so the particular variables must not have been very influential on the model (their elimination was warranted).

Although many of the new models used the 1.5 threshold, some used a slightly lower one (1.4 or 1.3), since each quality parameter model was handled individually.

The quality parameter models with set VIP thresholds were further reduced by removing variables which were highly covariant, leaving only the predictor variables

which significantly contributed to the percentage of variation in response variables. This iterative process was repeated until there was a significant decrease in the predictive power of the model. A strong covariance was identified using the Correlation Loading Plot (which displayed covariant predictor variables as highly clustered), similarities between VIP values (which suggested covariance), and knowledge of which predictor variables were combinations of other predictor variables (i.e. variables from stage 3.2 were also included in cumulative stage 4.2 and therefore would have some covariance). If the model's predicting power decreased significantly after deleting the predictor variable, it was determined to be important and retained.

Throughout the model development, the number of latent variables for each model was selected according to Tobias (1995). Latent variables or factors work to explain the maximum amount of variation in both the predictor and response variables by extracting combinations of the predictors (SAS Institute Inc. 2013a). The degree of success of the prediction is described with a root mean predicted residual sum of squares (PRESS) value (which basically measures the difference between the predicted and observed values), with lower PRESS values being favourable (SAS 2012). Once the final predictor variables for the reduced models were decided on, the models were run with alternative numbers of latent variables, in an effort to further increase the percentage of variation in response variables accounted for by the model predictor variables (despite models with greater numbers of latent variables being more complex models). Models which significantly increased their predicting power (the percentage of variation in response variables accounted for by the model predictor variables) by increasing the number of latent variables used the higher latent variables.

This resulted in two, three or four latent variables being used in the final reduced models for each quality parameter.

Each final predictive model was then expressed as parameter estimates of a linear equation with an intercept and adjusted coefficients (rather than the original centered and scaled data) for each of the selected predictor variables. These models each used a minimum number of predictor variables to explain the maximum percentage of variation within predictor and response variables. The variation that was not accounted for was expected to be a combination of genotype, genotype by environment interaction, producer management or environmental factors not considered within the model. However, since the effect of genotype and genotype by environment interaction was not quantified, there was the possibility of two interpretations of the results; one being that a greater percentage of variation accounted for by the model was indicative of a successful model and that most (or all) of the environmental effects were captured by weather parameters in the model. Conversely, another perspective is that the model's ability to account for a modest percentage of variation is the result of robust canola varieties which are not highly impacted by a range of growing season weather conditions.

3.4 Results

3.4.1 Statistical Analysis of Canola Quality by Data Subsets

The effect of dataset on canola quality parameters is shown in Table 3.10. Possible differences in field datasets (2009Field and 2009TDField) could be a function of location, (since all 2009TDField samples were collected in Manitoba) or management (most 2009TDField samples were grown in producers' fields, while most 2009Field samples were grown on research plots or fields and managed by seed

companies). While the two field datasets (2009Field and 2009TDField) only produced significantly different linoleic acid and total saturated fatty acids values, the fatty acids in the 2009TDField dataset generally had a much greater range in values (than the 2009Field dataset).

The differences between 2009All and 2008HS datasets suggest a year effect as glucosinolates, oleic acid, linolenic acid, saturated fatty acids and the iodine value appeared to suggest. The 2008 crop year produced significantly lower glucosinolates, linolenic acid and iodine values and significantly higher oleic and saturated fatty acids than the 2009 crop year.

Table 3.10. Canola quality by dataset.

Quality Parameter	Dataset							
	2008& 2009 HS	2008 HS	2009 All	2009 AllField	2009 Field	2009 HS	2009 TDField	All2008& 2009
Oil	45.05	44.94	45.40	45.57	46.43	45.34	44.17	45.09
Protein	20.10	20.28	19.85	20.50	20.10	19.62	21.15	20.14
Chlorophyll	11.44^{AB}	10.88^{AB}	11.02^{AB}	5.36^{C}	4.99^{C}	12.97^{A}	5.95^{BC}	10.92^{AB}
Glucosinolates	8.50^{B}	8.19^{B}	9.45^{A}	9.77^{A}	10.36^{A}	9.34^{A}	8.82^{AB}	8.61^{B}
Oleic acid	62.61^{CD}	62.97^{BC}	62.24^{DE}	63.97^{AB}	64.76^{A}	61.62^{E}	62.83^{ABCD}	62.73^{CD}
Linoleic acid	18.85^{AB}	18.69^{B}	18.85^{AB}	17.68^{CD}	17.03^{D}	19.28^{A}	18.62^{ABC}	18.74^{B}
Linolenic acid	9.41^{BC}	9.12^{C}	10.16^{A}	10.03^{AB}	10.10^{AB}	10.20^{A}	9.93^{ABC}	9.47^{B}
Saturated fatty acids	7.08^{AB}	7.16^{A}	6.75^{C}	6.42^{DE}	6.24^{E}	6.86^{C}	6.68^{CD}	7.02^{B}
Iodine value	112.55^{B}	111.82^{C}	114.2^{A}	113.33^{AB}	112.93^{ABC}	114.5^{A}	113.98^{ABC}	112.62^{B}
N	225	164	83*	22*	13	61	9*	247*

Values with the same letter across a row are not significantly different at 5% probability.
*These values are N-1 for Oil, Protein, Chlorophyll, Glucosinolates, and Iodine value

Chlorophyll had the largest range of values across datasets with both 2009Field and 2009TDField datasets producing significantly lower chlorophyll than 2008HS and 2009HS datasets. But there was no significant effect of year on chlorophyll values (shown by the comparison between 2008HS and 2009All).

Overall, dataset rankings for oleic acid were inversely related to those for linoleic acid (Ex. the dataset including the greatest oleic acid values also included the smallest linoleic acid values). Data rankings for saturated fatty acids were similar to those for linoleic acid, except for 2009HS (which was ranked higher for linoleic acid). Linolenic acid and the iodine value follow similar dataset rankings, except for the 2009Field dataset, which was ranked higher for linolenic acid.

There was no significant difference in oil and protein content across all datasets. However, the slightly higher oil content in 2009 (than 2008) was verified by the CGC Western Canadian harvest and export quality report (Barthet 2009).

Variety appeared to have no significant effect on protein and glucosinolates content, but did significantly affect oil, chlorophyll, iodine value, oleic, linoleic, linolenic, and saturated fatty acid content (Table 3.11). Most notably, varieties 5020, 7145, and SP Banner had significantly great oil content than variety 5030.

Table 3.11. Canola quality by variety.

Quality parameter	Variety					
	1841	**3465**	**5020**	**5030**	**7145**	**SP Banner**
Oil	44.79^{AB}	45.21^{AB}	45.42^{A}	43.68^{B}	45.13^{A}	46.28^{A}
Protein	20.95	19.70	19.81	20.78	20.53	19.50
Chlorophyll	16.55^{A}	15.91^{A}	10.95^{B}	10.72^{B}	9.05^{B}	8.90^{B}
Glucosinolates	8.30	8.08	8.96	8.28	8.21	8.92
Oleic acid	61.50^{B}	63.45^{A}	63.39^{A}	61.88^{B}	61.95^{B}	62.87^{AB}
Linoleic acid	19.39^{A}	18.09^{B}	18.25^{B}	18.42^{B}	19.98^{A}	19.33^{A}
Linolenic acid	9.85^{AB}	9.22^{BC}	9.44^{B}	10.43^{A}	8.87^{C}	8.97^{BC}
Saturated fatty acids	7.09^{AB}	7.13^{AB}	6.93^{BC}	7.21^{A}	7.13^{A}	6.73^{C}
Iodine value	113.76^{AB}	111.48^{B}	112.24^{B}	113.86^{A}	112.5^{B}	112.47^{AB}
N	11	15	110*	43	47	21

*These values are N-1 for Oil, Protein, Chlorophyll, Glucosinolates, and Iodine value

Not surprisingly, there was a wide range of chlorophyll values across varieties too, with 1841 and 3465 (which had the lowest number of observations out of all

varieties considered) producing significantly higher chlorophyll content than 5020, 5030, 7145 and SP Banner.

An inverse relationship of variety rankings between oleic and linoleic acid, first noted amongst datasets, was again apparent across varieties, except in the case of variety 5030. For example, the highest oleic and lowest linoleic acid values were found in varieties 5020 and 3465, while the lowest oleic and highest linoleic acid values were found in varieties 1841 and 7145.

Variety rankings for linolenic acid were similar to those for iodine value, except for proportionally higher 7145 and SP Banner iodine values. Interestingly, variety 5030 had the highest linolenic acid and iodine values, but also the highest saturated fatty acids values (despite linolenic acid and iodine values describing a high unsaturated fatty acid component). However, the range of saturated fatty acid values across varieties was very low (0.48), with less than 0.5 % saturated fatty acid content separating the values for variety 5030 and the values for the variety with the lowest saturated fatty acid values.

The open pollinated samples had higher chlorophyll, oleic acid and linoleic acid but lower protein, glucosinolates, and iodine value (Table 3.12). There was significantly higher oil content and significantly lower linolenic acid and saturated fatty acids in open pollinated samples (than hybrid samples). The hybrid samples were represented by 211 (210 for oil, protein, chlorophyll, glucosinolates and iodine value) samples compared to only 36 open pollinated samples.

Glucosinolates, oleic acid, linolenic acid content and iodine values were all greater in Liberty Link™ samples (than Round-Up Ready™ ones), while oil, protein, chlorophyll, and saturated fatty acids values were greater in RoundUp Ready™ samples. The only significant differences between the two types of germplasm were

amongst glucosinolates, oleic acid, linoleic acid, and linolenic acid values which were all greater in Liberty Link™ samples, except for linoleic acid.

Table 3.12. Canola quality by type and germplasm.

Quality parameter	Type		Germplasm	
	Hybrid	Open Pollinated	Liberty Link™	Round-Up Ready™
Oil	44.97^{B}	45.83^{A}	44.93	45.36
Protein	20.23	19.59	20.09	20.22
Chlorophyll	10.77	11.82	10.88	10.99
Glucosinolates	8.62	8.57	8.76^{A}	8.36^{B}
Oleic acid	62.66	63.12	62.96^{A}	62.35^{B}
Linoleic acid	18.73	18.81	18.30^{B}	19.46^{A}
Linolenic acid	9.54^{A}	9.07^{B}	9.72^{A}	9.06^{B}
Saturated fatty acids	7.04^{A}	6.90^{B}	7.01	7.04
Iodine value	112.71	112.06	112.7	112.48
N	211*	36	153*	94

*These values are N-1 for Oil, Protein, Chlorophyll, Glucosinolates, and Iodine value

Only linolenic acid had significantly greater values and saturated fatty acids had significantly lower values in cool samples. Although not significant, cool temperature samples had higher oil and lower protein than the warm temperature samples (Table 3.13). Surprisingly, oil content was significantly higher and protein content was significantly lower in low precipitation samples than in high precipitation samples. This could have been symptomatic of the definition of 'cool' and 'warm' temperatures rather than just the effect of lower versus warmer temperatures, as these specific results are not supported by the predictive model results. Precipitation had no significant effect on chlorophyll, glucosinolates, oleic acid, linoleic acid, linolenic acid, saturated fatty acids or iodine value, although the high precipitation samples had slightly higher chlorophyll, linoleic acid and saturated fatty acids than low precipitation samples.

Table 3.13. Canola quality by growing season air temperature and precipitation.

Quality parameter	Temperature		Precipitation	
	Cool	Warm	Low	High
Oil	45.27	44.92	45.42^{A}	44.71^{B}
Protein	19.99	20.27	19.88^{B}	20.43^{A}
Chlorophyll	10.55	11.28	10.86	11.00
Glucosinolates	8.76	8.47	8.74	8.46
Oleic acid	62.74	62.72	62.81	62.63
Linoleic acid	18.66	18.82	18.61	18.90
Linolenic acid	9.61^{A}	9.34^{B}	9.58	9.34
Saturated fatty acids	6.96^{B}	7.07^{A}	6.98	7.07
Iodine value	112.84	112.41	112.72	112.49
N	120	127*	132	115*

*These values are N-1 for Oil, Protein, Chlorophyll, Glucosinolates, and Iodine value

Lower oil and higher protein contents were found in canola samples grown in the southernmost latitudes of western Canada (49^{o} and 50^{o}N), although only samples from 49^{o} were significantly greater than 51^{o} samples for both quality parameters.

There were no significant differences in chlorophyll, iodine values, linolenic acid and saturated fatty acids across the range of latitudes. The lowest glucosinolates content occurred at 52^{o}N, for no obvious reason. There was a contradictory trend between oleic and linoleic acid again, where the lowest oleic values in the southernmost latitude range corresponded to the highest linoleic values (Table 3.14).

Table 3.14. Canola quality by the latitude of the sample site.

Quality parameter	Latitude					
	49^{o}	**50^{o}**	**51^{o}**	**52^{o}**	**53^{o}**	**54^{o} +**
Oil	44.15^{B}	44.64^{AB}	45.77^{A}	45.61^{A}	45.39^{A}	44.97^{AB}
Protein	20.61^{A}	20.51^{AB}	19.36^{B}	19.65^{AB}	20.32^{AB}	20.91^{AB}
Chlorophyll	11.26	12.51	10.36	10.69	10.19	9.11
Glucosinolates	8.91^{A}	8.61^{AB}	8.59^{AB}	8.06^{B}	9.03^{A}	9.09^{AB}
Oleic acid	62.23^{B}	62.54^{AB}	62.29^{AB}	62.97^{AB}	63.33^{A}	63.38^{AB}
Linoleic acid	19.28^{A}	18.85^{ABC}	19.12^{AB}	18.53^{BC}	18.16^{C}	18.19^{BC}
Linolenic acid	9.35	9.49	9.59	9.43	9.55	9.45
Saturated fatty acids	7.11	7.06	6.94	7.04	6.92	6.92
Iodine value	112.83	112.70	113.22	112.34	112.34	112.20
N	49*	46	34	66	37	15

*These values are N-1 for Oil, Protein, Chlorophyll, Glucosinolates, and Iodine value

3.4.2 Canola Quality Models

The models for weather impacts on each of the canola quality parameters are shown in Table 3.15. The predicting power for these models are shown in Table 3.16.

Table 3.15. Weather-based models for canola quality.

Quality Parameter	Predictive Model†
Oil	40.19353106 + (E_CD<14*0.29558084) + (CF_CD<14*0.01006754) + (BD_CD<11*0.02063818)
Protein	20.17862118 + (B_SDD>31*-0.6156292) + (D_SD>25*0.21016609) + (F_CDD<5*0.04952269) + (B_CD<8*0.13561434) + (CD_MaxT*0.16014171) + (E_CD<14*-0.30685188) + (BE_SumPrecip*-0.00908681) + (F_SDD>31*0.16154976)
Chlorophyll	-3.202145602 + (BD_‡WSI_tSum*0.012645512) + (DF_‡WSI_tSum*0.011192745) + (BD_MinT*0.227195994) + (D_SumPrecip*0.018092618) + (E_MinTCum*0.207560276) + (B_MinT*0.152537613)
Glucosinolates	8.550831821 + (CD_SDD>22*0.042183175) + (CD_AVET*-0.12563818) + (BF_CDD<17*-0.00121146) + (B_SDD>31*-0.410755207) + (F_SD>22CUM*0.021179128)
Oleic acid	60.67771103 + (C_CD<17*0.09680297) + (C_ET_oSum*0.01619112) + (C_SD>25*-0.1397951) + (F_CDD<5*-0.0332124) + (F_SD>28Cum*0.16786215) + (E_SumPrecip*-0.01371706) + (F_SD>19*-0.04767162) + (D_SDD>31*-0.04684707)
Linoleic acid	13.870211 + (E_‡WSI_tSumCum*0.00315917) + (CE_MinT*0.12077314) + (B_‡WSI_tSumCum*0.00464821) + (CF_MinT*0.08578915)
Linolenic acid	7.028414191 + (A_EToSum*0.012680338) + (EF_CDD<11Cum*0.003728524) + (CF_CD<5*0.032391417)
Saturated fatty acids	6.692359056 + (BF_CD<17*0.000203969) + (B_AveT*0.077056243) + (A_SDD>19*-0.001526846) + (B_MaxT*-0.000792041) + (A_ET_oSum*-0.004561666)
Iodine value	109.2604165 + (E_‡WSI_tSum*0.0092861) + (E_RangeTCum*-0.7982539) + (A_EToSum*0.0547394) + (F_CDD<5*0.0824621) + (D_SDD>31*0.0982094)

†Where A = phenological stage 3.2, B = phenological stage 4.2, C = phenological stage 4.3, D = phenological stage 4.4, E = phenological stage 5.2, F = phenological stage 5.4

‡WSI_t = WSI +400

Table 3.16. Percentage of variance explained by the predictors in final models.

Quality Parameter	Percentage of Variance Explained
Oil	25.5
Protein	38.7
Chlorophyll	6.6
Glucosinolates	43.5
Oleic acid	23.5
Linoleic acid	22.1
Linolenic acid	22.0
Saturated fatty acids	49.1
Iodine value	39.9

3.5 Discussion

3.5.1 Canola Quality

3.5.1.1 Oil Content. Interestingly, the comparison of means revealed that dataset, germplasm and temperature did not have a significant effect on oil content, but variety, type, precipitation and latitude did. Although not significantly different, the 2009TDField dataset, whose field trial sites were only across Manitoba, had the lowest oil content across samples. Alternatively, the 2009Field dataset, whose field trial sites were all across western Canada had the highest oil content. The low oil content from Manitoba sites is supported by Daun (2006), who found unexpected lower oil contents in Manitoba. He attributed this to the negative effect of higher (minimum and maximum) temperatures overriding the (positive) effect of higher average moisture content, combined with the negative impacts of higher available nitrogen associated with higher moisture content.

High precipitation samples produced significantly lower oil and significantly higher protein content than low precipitation samples. Surprisingly, there was no significant differencein oil or protein, between the high and low temperature samples. These results are not in agreement with conclusions made from the predictive models. They are also somewhat surprising in light of earlier studies across the Canadian prairies showing that temperature affects the canola oil content to a greater degree than precipitation (May et al 2010). These findings may be related to both 2008 and 2009 being fairly cool growing seasons (AAFC 2010) that lack the strong negative impact of extremely high temperatures (Aksouh et al. 2001). In addition, both 2008 and 2009 had average precipitation (AAFC 2010), which may have left a smaller difference between low and high precipitation subsets than noted in other studies (Pritchard et al. 2000). Alternatively, it is possible that the timing of the precipitation

was not coordinated with the physiological development of the plant and instead of benefitting the canola quality, it became a detriment. However, previous research has found a positive relationship between oil content and rainfall (Pritchard et al. 2000; Si and Walton 2004; Gunasekera et al. 2006b).

Canola samples collected at 49^{o} latitude had significantly lower oil content than samples from higher latitudes, with samples at 50^{o} and $54+^{o}$ producing lower oil content than canola samples in the mid-latitudes (51^{o}-53^{o}). Daun (2006) also noted that latitude had a significant impact on canola oil content in a study of western Canadian canola. The effect of latitude could be indicative of a genotype by environmental interaction, although not every variety was present at each degree of latitude. It could also be related to the variation in temperatures which generally occur across latitudes (typcially with lower temperatures at higher latitudes and higher temperatures at lower latitudes, in the Northern Hemisphere).

In addition to weather parameters (and potentially indirectly related to the low and high precipitation subsets) oil content can be affected by interactions of location, species, and nitrogen, or species and nitrogen (May et al. 2010). The seeding date may also have had some effect on the oil content (in this study), especially in relation to the synchronization of physiological development and appropriate seasonal conditions. In a related study, Gunasekera et al. (2006a) found that the time of sowing had a significant impact on seed yields, with early seeding resulting in longer growing and post-anthesis durations, and producing greater yields.

A negative relationship between canola oil content and growing temperature has been known for some time. Even rapeseed grown at as low as 10^{o}C after pollination produced higher oil content than plants grown at 16^{o}C (Canvin 1965). Yaniv et al. (1995) found that two varieties of *Brassica napus* grown under a $12/17^{o}$C

temperature regime produced higher oil content than those grown under a 17/22^{o}C regime. More recently, Daun (2006) found a significantly negative relationship between oil and June minimum temperatures. While the relatively cool Canadian climate highlights the positive impact of cool temperatures, the negative impact of heat is crucial to Australian climates, both in terms of duration and intensity. In one Australian study, Pritchard et al. (2000) determined for each 1^{o} increase in average maximum temperatures throughout seed maturation, there was a 0.38 per cent decrease in oil content in (winter) canola.

There was a strong inverse correlation between oil and protein content (r^2 = 0.7478) in this study, which is supported by several other experiments (Canvin 1965; Pritchard et al. 2000; Aksouh et al. 2001; Si et al. 2003; Chen et al. 2005, Daun 2006; Gunasekera et al. 2006b). These two components (oil and protein) make up a huge part of the canola seed, in addition to residue and water. Therefore, if the amount of residue in the seed decreases while the amount of protein remains the same, the concentration (or percentage) of protein will appear to increase, although the physical amount will remain the same. Similarly, an increase in oil quantity will result in both an increase in percentage of oil and decrease in percentage of protein (relative to total seed content), while the actual quantity of protein remains the same. Therefore, conclusions about the impact of specific environmental effects on oil or protein content should be handled carefully, so that the impact of environment on oil is distinguished from the impact of environment on protein concentration, rather than just to the presence of both (parameters) in the seed and the resulting indirect effect on one quality parameter due to an effect on the other.

However, this may not be an issue according to Si et al. (2003), who reported that both oil and protein concentrations could increase independently, if desired, since each parameter is expressed through different genetic traits.

The relationship between oil and protein has also been investigated via the sum of oil plus protein content. Naturally, breeding for increased oil and maintained protein content could cause this, as Daun (2006) pointed out in analysis that discovered a significant increase (of the sum of oil plus protein content) over the last 50 years, even when corrected for the shift (from *Brassica rapa*) to *Brassica napus.* Oil plus protein was also significantly affected by variety, interestingly with the top three varieties (for oil plus protein content) echoing the top three varieties for protein content. Alternatively, oil plus protein content was affected by location (expressed by province), with provincial rankings aligning with oil content rankings.

Oil production is a regular function of growth in an oilseed and therefore both higher oil content and higher yield would be expected under conditions that are conducive to growth and plant development. However, this does not necessarily mean that specific weather conditions which produce maximum oil content would also produce maximum yields. Interestingly, Kutcher et al. (2010) determined that temperature and precipitation had a highly significant effect on seed yield, with the strongest negative relationship between the number of days with maximum temperature above 30^{o}C throughout the year and seed yield, followed by the positive impact of precipitation and the negative impact of maximum and (growing-season-averaged) mean daily temperatures. They even went on to calculate that each degree increase in mean growing season temperatures resulted in approximately 7% loss in seed yield and each week with maximum temperatures above 30^{o}C caused a 12%

yield loss, while 10 mm of growing season precipitation resulted in a 2% increase in yield.

The total yield produced is not just one specific biochemical pathway, but the collaboration of several physiological processes working together (May et al. 2010). One of the processes carried out within the seed is the production of oil, and representing over 40% of the seed's final content (Daun 2006), oil production is integral to the plant. This was in agreement with Gunasekera et al. (2006a) who reported higher growing season rainfall, higher post-anthesis rainfall, higher pre-anthesis mean temperatures and lower post-anthesis mean temperatures may all have contributed to the greater canola yields.

Sometimes weather parameters which have a substantial impact on yield may also have a substantial impact on oil content. For instance, May et al. (2010) found that sites with the lowest yields (averaged over 3 years) and highest yields were the same sites with the lowest and highest oil contents, respectively. Under heat stress, high yield was correlated with higher oil concentrations, but lower protein and glucosinolates concentrations (Aksouh et al. 2001). Results from Gunasekera et al. (2006b) support the positive relationship between oil content and seed yield and the negative relationship with protein concentration, but they also determined that canola had a greater percentage increase in oil concentration per unit increase in seed yield than mustard genotypes, and lower percentage reduction in protein concentration per unit increase in seed yield. In addition to oil content, Daun (2006) also found a positive relationship between yield and chlorophyll, glucosinolates, free fatty acids, linolenic acid and saturated fatty acids contents along with a negative correlation with protein content. However, Chen et al. (2005) did not find any specific trend between canola yield and oil content other than the general observation that cool wet years

produced higher yielding canola with higher oil content amongst the varieties in their study.

Therefore, the low oil content in the high precipitation samples and the lack of difference between the cool and warm year samples are counterintuitive.

3.5.1.2 Protein Content. Protein concentration has been shown to be strongly affected by environment (Pritchard et al. 2000), even to a greater degree than genotype (Si et al. 2003). Despite some variation in protein values across varieties, the lack of significant effect of variety, type or germplasm on protein content in the current study, along with a significant effect of precipitation on protein content supports the findings of protein being more affected by environment than genotype from Si et al. (2003). However the significant impact of latitude and the lack of effect of dataset on protein suggest opposing conclusions about the genotype by environmental interaction.

The well-documented inverse relationship between oil and protein content (Triboi-Blondel and Renard 1999; Pritchard et al. 2000; Gunasekera 2006b) was noted by the rankings of protein content by latitude opposing the rankings of oil content by latitude, and by precipitation having opposite effects on the two quality parameters. However, the lack of temperature effect in the least squared means analysis contradicts both the conclusions from the predictive model and from other studies which have shown that temperature, rather than precipitation, is more crucial for protein content determination (Triboi-Blondel and Renard 1999; May et al. 2010). Daun (2006) found that July maximum temperatures impacted oil-free protein content, while Gunasekera et al. (2006b) found that average maximum pre-anthesis temperatures also affected protein concentration, increasing protein by an average of 0.63% for each 1^{o}C rise in average daily temperature.

Temperature can indirectly impact protein content as well, with elevated temperatures hastening maturity and shortening the flowering period (Aksouh-Harradj et al. 2006), which has been associated with higher protein values (May et al. 2010). Unfortunately, high temperatures sometimes occur concurrently with low moisture, causing stress to the plant. Plants use stomatal closure to reduce the amount of transpiration from leaves and reduce water loss (under water deficient conditions) and stomatal opening for transpiration to cool off (under hot conditions) (Taiz and Zeiger 2006). Therefore, low precipitation at a time when moisture is still needed for growth and development, would accentuate the effects of heat stress. As an oilseed crop, canola prefers oil as an energy storage molecule and attempts to produce over 40% oil before putting photosynthates into protein. However, since oil production requires water (Taiz and Zeiger 2006), lack of precipitation may trigger canola to produce more protein as an alternate energy storage sink.

The combination of temperature and precipitation can have a concerted impact on protein, too. Often studies group weather into cool and wet or hot and dry conditions (Triboi-Blondel and Renard 1999; Pritchard et al. 2000), making it difficult to define the impact of each variable on its own. For instance, Prichard (2000) determined that cool and wet conditions were associated with low protein values while hot and dry conditions (as represented by various regions in the country) were associated with high protein values. Similarly, Triboi-Blondel and Renard (1999) found that cool, irrigated canola produced significantly lower protein values than hot, water-stressed canola.

There are some conflicting conclusions about the effect of precipitation accumulation on protein content, with Pritchard et al. (2000) finding that rainfall did not have a significant effect on seed protein, Gunasekera et al. (2006b) determining

that total (growing season) rainfall and post-anthesis rainfall helped explain the variation in protein content, and Si et al. (2003) finding that rainfall had no significant effect on the protein concentration of canola meal except when data was pooled across early and mid-season maturity groups.

In support of the significantly lower precipitation areas producing lower protein values in this study, Gunesekera (2006b) found that rainfall was negatively correlated with protein (r^2 = -0.69) and that protein concentration increased 0.11% per millimetre reduction of rainfall across all mustard and canola genotypes tested and in all environments. In addition, Triboi-Blondel and Renard (1999) determined that under the same high temperatures (a 26^{o}C day/18^{o}C night regime) canola produced greater protein content in the water-stressed conditions than the irrigated conditions.

However, precipitation effects on protein content are not isolated interactions. Precipitation interacts with the soil and plant affecting nutrient availability (MAFRI 2013b). Availability of nitrogen in relation to its potential movement in the soil is influenced by soil moisture content, where adequate moisture content allows for movement of the nutrient and potential plant uptake (as opposed to excessive moisture, which would cause nitrogen leaching). In turn, the amount of nitrogen the plant receives during development has been shown to influence final protein content (Canvin 1965). More specifically, protein concentrations have been shown to be positively affected by nitrogen rates (in terms of rates applied to the soil) and location by nitrogen interaction, among other variables (May et al 2010). This relationship is finite, though, as some level of moisture eventually begins leaching the nitrogen and becomes a problem (Thomas 1995).

3.5.1.3 Chlorophyll Content. A significant difference in chlorophyll content by variety suggested a genotypic effect, but the lack of significant effect by type or

germplasm did not confirm this. The effect of variety (genotype) on chlorophyll content has been recorded (Ward et al. 1995; Daun 2006) as well as a lack of effect (Rakow and McGregor 1975). Not only the variety, but the species has an effect on chlorophyll, according to Daun (2006). He suggested that the shift in canola varieties from *B. rapa* to *B. napus* is partly responsible for the increase in the average level of chlorophyll that has occurred over the last twenty years, since *B. napus* varieties have higher background chlorophyll and a longer growing season and less determinate flowering (Daun 2006) which can lead to limited time for chlorophyll degradation.

There was no significant difference in chlorophyll between the warm and cool temperature samples, between the high and low precipitation samples, or by latitude (which can indirectly show the effect of environment or genotype by environment interactions). These findings oppose conclusions from the predictive model in this study, and Daun (2006), who reported chlorophyll was highly weather dependent.

Mature rapeseed contains low levels of chlorophyll, however unfavorable harvesting conditions have been associated with higher, less desirable levels of chlorophyll (Appelqvist 1971). Therefore, it would be expected that cool temperatures or more northerly locations (high latitudes) with delayed maturity would increase the risk of higher chlorophyll. However, cool temperature samples had (insignificantly) lower chlorophyll values, and the latitudes of 51^{o} and greater also produced insignificantly lower chlorophyll values than 49^{o} and 50^{o} latitudes. One explanation for this may be the increased day length at higher latitudes, where the greater number of heat units provided each day balances out the shorter frost-free period, resulting in an adequate accumulation. Furthermore, the extended growing season could maintain elevated chlorophyll content due to delayed senescence. Alternatively, the increased risk of frost before the seed has a chance to senesce, or the

result of germination and sprouting in the swaths can result in high chlorophyll content. However, the current study did not reveal any systematic trend in chlorophyll levels as a result of temperature, precipitation or latitude.

The lack of difference between the 2008HS and 2009All datasets suggest that year did not have an effect on chlorophyll content. However, the significantly lower chlorophyll content in field datasets (2009Field and 2009TDField) than the CGC Harvest survey dataset (2009HS) propose that either location (Manitoba), plot size or management may have affected chlorophyll content. An effect of location on chlorophyll was also noted by Daun (2006).

It should also be noted that the range in values between datasets demonstrate the magnitude of variability across chlorophyll samples. The maximum range between two chlorophyll content samples was over 25, and with the highest standard deviation (and variance) among quality parameters, the expression of chlorophyll content appeared to be dependent on the environment, similar to findings from Ward et al. (1995) and Daun (2003). However, the huge amount of variation may have created a "noisey" dataset with and a lack of significance.

3.5.1.4 Glucosinolates Content. Unlike chlorophyll, the total range of glucosinolates content in the canola samples in this study was very small (4.6 to 13.4 μmol g^{-1}) with the majority falling between 7 and 10 μmol g^{-1} (Appendix 3). This range is much lower than Bahrani and McVetty (2007) found between plants within the same treatment in a single experiment and is well below the "less than 18 micromoles of total glucosinolates per gram of whole seed at a moisture of 8.5%" (Daun and Adolphe 1997) required to classify it as canola. Glucosinolates content was not significantly different by variety, type, temperature or precipitation, but did exhibit significant differences between datasets, germplasms and latitudes. Excluding

the year effect between 2009HS and 2008HS datasets, these results were inconsistent and did not provide any guidance as to why the differences occurred.

The contradiction of significant and insignificant effects of germplasm and variety on glucosinolates was not expected, since successful breeding efforts which have collectively decreased glucosinolates content in both the long term (Daun 1986) and more recent history (Barthet 2009). The highly significant impact of genotype on final glucosinolates content has been determined in hot, dry climates (Mailer 1989; Pritchard et al. 2000), but Bahrani and McVetty (2007) concluded that there is still room for improvement in the canola breeding programs (in reference to glucosinolates).

The significant difference between datasets and latitude may be representative of both the effect of location, which is supported by Mailer (1989) and environment, supported by Pritchard et al. (2000). This has been shown to have an impact across western Canadian crops, both at a provincial level with Alberta producing greater values than both Saskatchewan and Manitoba (Barthet 2009) and at a micro-climate scale (Wentzell and Kliebenstein 2008). While the differences between provincial content may be partially attributed to temperature and precipitation conditions, the micro-climate is affected by soil nutrients, plant density and herbivory (Wentzell and Kliebenstein 2008).

Despite a lack of effect of temperature on glucosinolates content from the least squared means tests, a positive relationship between heat and glucosinolates content is supported by several studies (Aksouh et al. 2001; Aksouh-Harradj et al. 2006; Bahrani and McVetty 2007). The predictive model in this study also described positive relationship between glucosinolates and heat late in the season.

Short bursts of extremely hot temperatures (40^{o}C) at from 29 to 34 DAF especially affected glucosinolates, producing significantly higher glucosinolates than the control at a moderate temperature (21^{o}C day/16^{o}C night regime) (Aksouh et al. 2001). Since maximum temperatures in the current study did not reach such extreme temperatures, similar effects on glucosinolates could also not be expected.

Another explanation for the lack of significant temperature effect on glucosinolates may be partially due to heat having less of an impact on glucosinolates synthesis than other seed components. Conversely, in a controlled study where heat tolerant canola varieties were provided adequate water, glucosinolates content was not significantly affected by heat treatments, and actually showed a slight decrease in content in seeds from the main stem (Aksouh-Harradj et al. 2006). The reason for this discrepancy may be related to the variety, or the controlled environment preventing any additional stress to the plant that may occur in a field setting (ex. high evapotranspiration rates causing reduced moisture). However, the fact that glucosinolates levels tend to be higher in the warm canola-growing regions of Australia than the cooler regions in western Canada, suggests that higher temperature increase glucosinolates levels (Pritchard et al. 2000). This trend may also be indirectly related to the positive relationship between glucosinolates and protein content (partly due to both of their relationships with plant nitrogen and sulfur content).

The intensity of heat may even have more impact than the corresponding to growth stage over which it is measured, since seeding date alone has not been shown to affect final glucosinolate content in canola seeds (CCC 2013c).

3.5.1.5 Fatty Acid Profile. Total oil content results from the synthesis of several fatty acids, including unsaturated (ex. oleic, linoleic, and linolenic acid) and saturated

fatty acids. The two weather conditions which play an important role in fatty acid production are temperature and precipitation. Cool, wet conditions favour greater oil production (Yaniv et al. 1995; Deng and Scarth 1998; Bahrani and McVetty 2007) and progressively higher temperatures favour the production of more saturated fatty acids over the production of unsaturated fatty acids (Canvin 1965). While precipitation can independently impact oil content (Triboi-Blondel and Renard 1999; Pritchard et al. 2000), it is rarely a major consideration in individual fatty acid studies (Trémolières et al. 1978; Yaniv et al. 1995; Deng and Scarth 1998).

The final expression of a quality parameter can be the result of several complex contributing factors (or processes), which in some cases may even oppose one another. Therefore, the correlation between the (potentially overriding) weather parameter and a fatty acid quality parameter is dependent on both the type (degree of saturation) of fatty acid and the quantity that the fatty acid contributes to the total oil content. Oleic acid, for example, is a mono-unsaturated fatty acid (only one double bond away from saturated fatty acids) that accounts for at least 60% of total oil content. The cool, wet conditions favour the fatty acid in terms of the amount of total oil that is produced, while the high temperatures favour the fatty acid in terms of its low degree of unsaturation (close proximity to saturation). Despite fatty acids of varying degrees of unsaturation all contributing to total oil content, fatty acids with greater degrees of unsaturation account for lower percentages of total oil content (ex. linoleic acid at ~20%, linolenic acid at ~10% versus oleic acid at ~60%). Unsaturated fatty acids tend to only be impacted by weather conditions which favour a greater degree of unsaturation. Meanwhile, oleic acid, which accounts for the majority of oil content, is affected both by weather conditions that favour a lower degree of unsaturation (closer to saturation) and conditions that favour total oil production.

Saturated fatty acid content and iodine value are primarily affected by the conditions which impact the level of saturation in the oil (rather than the contribution to oil content). Canvin (1965) hypothesized that high temperatures did not just accelerate the conversion from fatty acids with a greater degree of unsaturation to those with a lesser degree of unsaturation (favouring oleic acid production rather than linoleic or linolenic acid). He proposed high temperatures actually inactivate the enzymes responsible for producing unsaturated fatty acids.

Unfavorable environmental conditions, such as heat stress or water deficiencies will tend to shift the production from linoleic or linolenic fatty acids toward oleic fatty acids. However, the degree of shift from oleic to linoleic or linolenic fatty acids is limited because oleic acid makes up such a huge portion of total oil content. Oleic acid is accumulated more uniformly throughout plant development because it dominates the total oil content. A number of early papers on canola quality, including one by Stefansson and Storgaard (1969), identified a strong negative relationship between oleic and erucic acid. Canola breeding has almost completely eliminated erucic acid from the fatty acid profile of canola. Since only trace amount of erucic acid were found in the samples in the current study, further anaysis with this fatty acid was not investigated.

3.5.1.6 Oleic Acid Content. There was a significant effect of dataset, variety, germplasm and latitude on oleic acid content, but no significant effect of type, temperature or precipitation. The difference between datasets may be partly explained by a year effect, since 2008HS and 2009All datasets were significantly different, although with 2009Field and 2009TDField significantly higher than 2009HS, the field datasets really brought up the final 2009All value more than the 2009HS dataset.

The difference between latitudes could be due to a genotype by environmental interaction. A genotype by environmental interaction may have been to the reason behind two varieties (HEAR and LEAR varieties) reacting differently to two temperature regimes, with one variety producing significantly greater content at the higher temperature regime and the other variety producing the same amount (Yaniv et al. 1995). However, this is not supported by Aksouh-Harradj et al. (2006) who found oleic acid was not significantly affected by genotype by environment interaction in both the main stem and bulk of canola.

The significant effect of variety and germplasm in the current study is not surprising, since the effect of genotype has been found to be significant in other studies (Pritchard et al. 2000). Early breeding efforts reported that the shift (from high) to low or zero-erucic acid varieties also resulted in much higher oleic acid content and an increase in the final linoleic and linolenic acid contents (Downey and Craig 1969). This is due to a strong negative relationship between the synthesis of erucic acid and oleic acid in early canola varieties, which had much higher erucic acid content (Craig 1961) than current varieties (which have continued to minimize erucic acid content in the last decade) (Barthet 2009). Modern breeding efforts continue to drastically alter oleic acid content in varieties (Yaniv et al. 1995).

The lack of precipitation effect on oleic acid content is in agreement with Pritchard et al. (2000), but the lack of temperature effect was contradictory to the results of the predictive model and many other studies. More specifically, Canvin (1965) found canola grown at 10^{o}C produced greater oleic acid content than plants grown under 16^{o}C. Elevated oleic acid content in canola grown under a cooler temperature regime was observed in conventional (Deng and Scarth 1998) and low-

linolenic acid rapeseed varieties (Baux et al. 2008), along with increased in oil content (Deng and Scarth 1998).

3.5.1.7 Linoleic Acid Content. With an aggregated mean value of 18.7%, linoleic acid was the second most prominent fatty acid (after oleic acid) investigated, with the second largest variance, range and standard variation among fatty acids measured (Appendix 3). There was a significant effect of dataset, variety, germplasm and latitude on linoleic acid content, but no significant impact of type, temperature, or precipitation. Despite the lack of significant difference between variety types, the impact of variety and germplasm highlight the importance of genotype, which Pritchard et al. (2000) also found to have a significant effect on linoleic acid content. In fact, breeding efforts have successfully manipulated several aspects of the fatty acid profile in order to produce varieties with a selection of linoleic acid contents, including high linoleic and low linolenic acid (Deng and Scarth 1998), high linoleic acid (Trémolières et al. 1982), or high oleic low linolenic acid (Baux er al. 2008) varieties.

Year did not have a significant impact on linoleic acid content, but the difference between the 2008&2009HS dataset and the 2009AllField datasets suggest that either producer management or non-weather related environmental conditions (such as soil) had a significant effect on linoleic acid content. The difference in datasets and the significant effect of latitude could also be due to genotype by environmental interactions. While no genotype by environmental interaction could be inferred from Yaniv et al. (1995) and almost no interaction could be determined from Deng and Scarth (1998), it was significant in the main stem of canola plants in Aksouh-Harradj et al. (2006).

The lack of temperature and precipitation effect on linoleic acid is not surprising, as environmental impacts on linoleic acid have not always been quantified and even the predictive model in this study only selected four parameters to explain the variation in content. Alternatively, some studies have been unable to identify a significant impact of temperature or rainfall on linoleic acid (Pritchard et al. 2000; Aksouh et al. 2001; Baux et al. 2008). The reason for these conflicting conclusions may be due to linoleic acid's role as an intermediary fatty acid along the progression from saturated to increasingly unsaturated fatty acids (between oleic and linolenic acid). As a result, it is likely affected by both conditions which impact oleic acid and linolenic acid content. In support of this hypothesis, Baux et al. (2008) found that although temperature did not have a significant effect on linoleic acid content, oleic and linolenic acid had strong relationships with minimal daily temperatures. Furthermore, both the desaturation reactions of oleic acid to linoleic and from linoleic to linolenic were temperature sensitive. Under low temperatures oleic acid was driven to produce linoleic acid, which would then go on to produce linolenic acid, resulting in both a decrease in oleic acid content and increase in linolenic acid content, and no change in linoleic acid content (Baux. et al. 2008).

3.5.1.8 Linolenic Acid. There were significant effects of variety, type, and germplasm on final linolenic acid contents, suggesting a strong effect of genotype. The impact of genotype on linolenic acid content is supported by Pritchard et al. (2000) and may be symptomatic of successful breeding efforts to alter linolenic acid content. Despite being a healthy omega-3 poly-unsaturated fatty acid (CCC 2011a), linolenic acid can be undesirable for its highly oxidative qualities which lead to rancidity (Przybylski 2011). The increased breeding efforts, which have successfully

yielded low-linolenic acid varieties (Deng and Scarth 1998) are evidence that genotype may have a substantial effect on the expression of linolenic acid.

Significant differences between datasets 2008HS and 2009All point toward a year effect on linolenic acid content, with the field datasets (2009Field and 2009TDField) bringing the mean value for 2009 down. The significant difference between years is supported by Barthet (2009). With the difference between datasets largely explained by year effect, and no significant impact of latitude, it may be concluded that genotype by environment interaction had little impact on linolenic acid content, just as Aksouh-Harradj et al. (2006) found.

Unlike oleic and linoleic acid, there was a significant effect of temperature on linolenic acid content, with warm temperature samples producing lower linolenic acid content than cool temperature samples. Several studies have identified the same negative relationship with temperatures (Canvin 1965; Trémolières et al. 1978; Trémolières et al. 1982; Yaniv et al. 1995; Deng and Scarth 1998; Baux et al. 2008), including Daun (2006), who found that long cool seasons resulted in higher linolenic acid content. Deng and Scarth (1998) credited the high temperatures for hastened maturity and reduced activity of the desaturase enzymes which resulted in low linolenic acid content.

3.5.1.9 Saturated Fatty Acid Content. Saturated fatty acid content encompasses several individual fatty acids, of which the most prominent ones are palmitic, stearic, archaridic and behenic (Aksouh-Harradj et al. 2006). Some fatty acids may be affected slightly differently under certain environmental conditions which may make it difficult to ascertain the impact of environment on total saturated fatty acid content.

Despite a lack of difference among germplasms, the significant differences in saturated fatty acid content among type and varieties, with 5030 and 7145 RR

producing the highest values and SP Banner producing the lowest values (which could not be attributed to the production company or the year in which the variety was released), suggest a genotypic impact. This significant effect of genotype on saturated fatty acid content has been determined in several other studies (Pritchard et al. 2000; Aksouh et al. 2001; McCartney et al. 2004; Aksouh-Harradj et al. 2006). Although this study investigated saturated fatty acids as a group, some studies draw conclusions about individual saturated fatty acids, which could help explain these effects. Pritchard et al. (2000) determined that genotype had a significant effect on palmitic acid, and McCartney et al. (2004) found that the variation in palmitic acid content explained more of the variation in total saturated fatty acids, than any other individual saturated fatty acid considered in the study (stearic, archidic or behenic acid).

While varieties may have breeding successes to thank for the recent decline (1998-2009) in total saturated fatty acid content of canola, No.1 Canada grown across western Canada (Barthet 2009), Daun attributed the preceding increase in total saturated fatty acid content (1984-1998) to the species of *Brassica* grown (with *B. napus* containing higher saturated levels than *B. rapa*).

The significant effect of year on saturated fatty acid content was exhibited by the difference between 2008HS and 2009All datasets. The slightly lower saturated fatty acid content in 2009 (than 2008) reported in this study was confirmed by Barthet (2009).

With the difference between datasets being explained by the year effect, and no significant effect of latitude, it may be presumed that there was little impact of genotype by environmental interaction on saturated fatty acids. This conclusion of stability across environments has been reported in other studies (McCartney et al.

2004; Aksouh-Harradj et al. 2006; Daun 2006) and may be due to successful breeding programs which produce low total saturated varieties.

Amongst environmental parameters, precipitation did not have an effect on saturated fatty acid content, although high precipitation did have insignificantly higher values than low precipitation samples. Saturated fatty acid content was significantly lower in cool temperature samples, possibly because high temperatures can hinder the desaturation process and result in lower unsaturated fatty acid and higher saturated fatty acid content (Canvin 1965). This positive relationship between temperature and saturated fatty acids is supported by other research (Pritchard et al. 2000; Aksouh et al. 2001; McCartney et al. 2004; Aksouh-Harradj et al. 2006). While the current study groups all saturated fatty acids together so the impact on individual saturated fatty acids is unknown, McCartney et al. (2004) found that environment had more of an impact on stearic, archidic and behenic fatty acids, than palmitic acid.

3.5.1.10 Iodine Value Content. The iodine value is a measure of unsaturation of fatty acids and is expressed as the number of grams of iodine absorbed by a 100 gram sample (AOCS 2013), in this case, of canola oil. Higher iodine values represent a greater percentage of unsaturated fatty acids, such as varieties with high linolenic acid (Daun 1981) and low oleic acid content. Therefore it would be expected that iodine values would increase under conditions that favour both increased linoleic or linolenic acid production and inhibit saturated fatty acid production. However, neither temperature nor precipitation was found to have a significant impact on iodine values. Similarly, DeClercq (2008) determined that the effect of precipitation on iodine value was not always consistent. But dissimilar to the current study, he found that the effect of temperature was generally consistent. Cold temperatures were associated with high iodine values and hot temperatures were associated with low iodine values (DeClercq

2008). In a more general conclusion, Daun (1981) determined environment could explain some of the variation in iodine values of canola samples from northern and western regions in the Canadian Prairies.

Canola oil with high iodine values represent oil with a greater degree of unsaturation, which is also less stable. For this reason, breeding efforts over the past twenty years have not only focused on an oil profile with lower saturated fatty acid content for health benefits, but also maintaining a fatty acid profile which is not too unstable, in order to avoid oxidation that may lead to rancidity. The success of these breeding efforts may also be the reason the iodine value varied significantly by variety. Surprisingly, type and germplasm did not significantly impact iodine value. Further breeding and the creation of low erucic acid rapeseed (in the seventies) resulted in an increase of iodine values (Daun 1981), (which was attributed to the subsequent increase in linolenic acid content) and emphasized the influence breeding can have on different varieties. Recently, low-linolenic acid (and more commonly) high-oleic, low-linolenic acid varieties have continued to lower iodine values (Siemens and Daun 2005).

In addition to varietal differences, iodine value can vary by species with higher iodine values in Polish species (*Brassica campestris,* which was later called *Brassica rapa*) associated with higher values than Argentine (*Brassica napus)* varieties (Tkachuk and Kuzina 1976). This difference between species was suggested to be a main contributor to the drop in iodine values in Canadian canola samples initially between the eighties and mid to late nineties, when producers began producing much more *Brassica napus* than *Brassica rapa* (Siemens and Daun 2005; DeClercq 2008).

The impact of datasets can be attributed to the year effect, by the significant difference between 2008HS and 2009All. The iodine values were greater in 2009

values (compared to 2008 values) both in this study and the report by Barthet (2009). There was no significant difference in iodine value between samples across latitudes, which could be representative of a lack of genotype by environmental interaction.

3.5.2 Canola Quality Models

3.5.2.1 Oil Content. The three weather parameters which were best able to explain the variation in oil content among canola samples were the greatest number of days during phenological stage 5.2 with temperatures below 14^{o}C (E_CD<14), the greatest number of days during phenological stages 4.3 through 5.4 with temperatures below 14^{o}C (CF_CD<14), and the highest number of days during phenological stage 4.2 through 4.4 with temperatures below 11^{o}C (BD_CD<11). All of the weather parameters in the model were related to temperature, with weather parameters favouring a negative relationship between temperatures and oil content, as supported by Daun (2006).

This model was able to explain 25.5% of the variation in total oil content with weather parameters, leaving 74.5% of the variation to potentially be explained by genotype or genotype by environmental interactions (or additional environmental effects not considered by model). The predicting power of this model could be lower than some of the other quality parameter models because of a strong genotypic effect on oil content, rather than a deficiency in the predictive model. The relatively low range and standard deviation across all the oil content values, the significant differences between varieties and the significant differences between types of canola samples support the concept of strong genotype effect. This is in agreement with many other studies which have reported a significant genotypic effect on oil content (Si et al. 2003; Aksouh-Harradj et al. 2006; Daun 2006; Gunasekera et al. 2006b). This impact may not be surprising since oil content is the most valuable canola quality

parameter (Daun 2006) and has been a breeding priority for decades (Sernyk and Stefansson 1983). However, since the difference between varieties (in this study) could not be attributed to the production company, type, or the first year the variety was brought to the market, it is likely that the entire (seed production) industry has ranked this quality parameter as a priority and all seed production companies are increasing oil content in canola varieties (at a similar rate). This finding may be related to the variety registration process for all Canadian cultivars, which naturally selects for specific criteria such as consistent expression of quality parameters grown in varying environments.

The oil content of canola samples in this study were found to be the most responsive to weather parameters measured throughout phenological stages 4.3 through 5.2. These stages may have impacted final oil content because a portion of this duration corresponds to the majority of oil production (Fowler and Downey 1970; Perry and Harwood 1993). In addition to general oil production, the rapid increase in oleic, linoleic and linolenic fatty acid content generally occurs over 14 to 28 days after pollination (DAP) (which is roughly equivalent to phenological stages 4.3 and 4.4) (Fowler and Downey 1970). The low temperatures throughout this period (as noted by the inclusion of parameters BD_CD<11 and CF_CD<14,) may impact oil production by providing desirable temperature conditions for enzymes involved in the production, and thereby also favouring oil production over protein production.

The positive relationship between low temperatures throughout phenological stages 4.3 through 5.2 and oil content was echoed by Si and Walton (2004), who found a significant correlation between oil concentration and the post-anthesis duration, in which oil content increased by 1.2% for every 10 additional days of post-anthesis duration. Further support is given in May et al. (2010), who reported that

high oil content was associated with longer flowering periods. This may be as a result of the indeterminate flowering pattern of canola plants, which allows more young pods to develop in a longer post-anthesis period and increases the length of the critical oil accumulation window (Hocking and Mason 1993). Alternatively, Aksouh-Harradj et al. (2006) stated that canola in one region in Australia usually flowered between the limited range of 40 to 50 days, though this could be due to climate or other environmental restrictions (available soil moisture) in the area.

Low temperatures also discourage respiration, (and therefore) reduce moisture loss, favour the appropriate oxygen and CO_2 concentrations, and reduce allocation of photosynthates to growth-related activities (ex. root growth to access adequate moisture). In addition, the presence of low temperatures means the avoidance of higher temperatures, which would increase the rate of respiration and moisture loss, produce unfavourable concentration of CO_2, and reduce the activity of enzymes responsible for oil production (Appelqvist 1968; Ohlrogge and Jaworski 1997; Qaderi and Reid 2005).

The sensitivity to low temperatures through phenological stage 5.2 may also be due to the timeframe of the stage corresponding to oil content peaking, the rate of oil accumulation slowing down (Baux et al. 2008) and the total weight of oil (more specifically, triacylglercols) potentially even reducing slightly as the fresh weight of the seed decreases (Fowler and Downey 1970; Perry and Harwood 1993). At the whole plant scale, phenological stage 5.2 is characterized by the time when seeds in lower pods change from green to yellow or brown (Thomas 1995). The low temperatures may be effective in maintaining the conditions which are suitable for enzymes responsible for oil production and therefore even prolong oil production later into phenological stage 5.2.

The end of phenological stage 5.2, which corresponds to the end of seed development, involves the dehydration of the seed. Although this is a necessary step in development, higher temperatures may result in greater dehydration of the seed, while lower temperature may cause less dehydration and leave greater oil content (Perry and Harwood 1993). Dehydration may also explain the slight reduction in content of some individual fatty acids as the plant approaches phyical maturity (Fowler and Downey 1970; Perry and Harwood 1993).

The synchronization of weather conditions and plant developmental stages is critical to final oil content, as shown by the selection of specific phenological stage(s) for each weather parameter selected in the oil content model. Using calendar days as a chronological reference, Daun (2006) identified that June minimum temperatures had a significantly positive impact on oil content and May et al. (2010) reported the highest oil content values at locations with the lowest average August and September temperatures (approximately corresponding to phenological stage 5.2 or early 5.4). Regarding high temperatures, moderate and intense heat treatments over 20 to 29 days after flowering (DAF) and 25 to 29 DAF (roughly equivalent to late phenological stage 4.4) have been shown to have a slightly negative, or even a positive impact on oil content (Aksouh-Harradj et al. 2006), while moderate and intense heat treatments provided later in development (29 to 34 DAF, equivalent to phenological stage 5.2) have been reported to have a significantly negative effect on oil concentration (Aksouh et al. 2001). Similarly, Pritchard et al. (2000) found warm temperatures throughout seed maturation produced low oil content in a field study.

While the initial statistical analysis in this study did not find a significant difference between the warm and cool temperatures, the cool temperatures subset did have (insignificantly) higher oil content than the warm temperature subset (similar to

the relationship determined by the model). This trend is supported by many other studies (Canvin 1965; Yaniv et al. 1995; Pritchard et al. 2000; Si and Walton 2004; Gunasekera et al. 2006b). However, this finding could also be related to the high amount of variation within a variety in this study.

The positive impact of low temperatures on oil content focussed on temperatures within the 11^{o}C to 14^{o}C range. Although this span of values is on the low end of the optimal range of temperatures for seedlings (Thomas 1995), minimum temperatures (Pritchard et al. 2000; Daun 2006), and low temperatures of 10^{o}C (Canvin 1965) or temperatures regimes of 15^{o}C/10^{o}C, (Deng and Scarth 1998) 12^{o}C /17^{o}C, (Yaniv et al. 1995) and 18^{o}C/10^{o}C (for a winter canola variety) (Triboi-Blondel and Renard 1999) have also reported positive relationships with oil content. Further support was shown by a study which determined the highest frequency of daily minimum temperature values below 13^{o}C (between 41-60 DAF) had a strong (r^2 = 0.85) relationship with the linolenic acid content (in low-linolenic rapeseed) (Baux et al. 2008). Since daily low temperatures generally occur at night in western Canada, the impact of temperatures below the 11^{o}C to 14^{o}C range could also be related to the time of day that they were measured at. In support of this concept, Kutcher et al. (2010) found that yield reductions were associated with higher nocturnal temperatures and yield increases occurred in years with lower nocturnal temperatures.

The preference for low temperatures also implies a negative impact of high temperatures on oil content, which has been confirmed in other studies (Canvin 1965; Aksouh et al. 2001; Gunesekera 2006b). Morrison (1993) also reported that the late bud to early seed development stage (roughly equivalent to phenological stages 4.4 or 5.2) was the most sensitive to heat stress. Similarly, Si and Walton (2004) reported a negative correlation between oil concentration and post-anthesis mean daily

temperatures, noting a 0.68% drop in oil content for each additional degree between temperatures 11.5^{o}C to 18.5^{o}C. Gan et al. (2004) also determined that heat and water stress applied at the pod stage (corresponding to phenological stage 4.4), caused more physiological stress (total fertile pods per plant, total seed yield, seeds per pod and seed weight) than stress applied at the bud or flower stages, of four *Brassica* species.

The lack of effect of precipitation along with prominent temperature effects described by the oil content model could be the result of adequate growing season moisture across western Canada, as Si and Walton (2004) alluded to in a study where adequate rainfall sites were not as sensitive to post-anthesis rainfall as low rainfall sites, and a warm site was more sensitive to post-anthesis temperature than a cool site. In addition, May et al. (2010) reported that high oil content was associated with higher water use, but not necessarily higher precipitation. However, since only canola that graded Canada No.1 were used in this study, canola grown under extreme conditions with excess precipitation (and subsequent disease problems) or extreme heats would likely have quality issues (such as shrunken or broken kernels) and not attain No. 1 grade, and therefore be excluded from the study.

As previously mentioned, the impact of oil plus protein content has been examined by Daun (2006). Not only did he find a varietal and locational impact on this value, but also a negative correlation to August minimum temperatures (where lower minimum temperatures in August were associated with higher sums of oil plus protein content). Of course, this is separate from the prominent effect of June minimum temperatures on oil content and the effect of July maximum temperatures on protein.

3.5.2.2 Protein Content. The model selected eight weather parameters to explain the maximum variation in protein content among canola samples. In order of importance,

the weather parameters which promote higher protein contents were: the lowest number of stress degree days above the 31°C threshold throughout phenological stage 4.2 (-B_SDD>31), the highest number of stress days above the 25°C threshold throughout phenological stage 4.4 (D_SD>25), the highest number of cold degree days below the 5°C, throughout phenological stage 5.4 (F_CDD<5), the highest number cold days below the 8°C threshold throughout phenological stage 4.2 (B_CD<8), the highest maximum temperatures throughout phenological stages 4.3 and 4.4 (CD_MaxT), the lowest number of cold days below the 14°C threshold during the phenological stage 5.2 (-E_CD<14), the lowest precipitation accumulation throughout phenological stages 4.2 through 5.2 (-BE_SumPrecip), and the highest number of stress degree days above the 31°C threshold throughout phenological stage 5.4 (F_SDD>31). The overall trends that emerge from this selection of weather parameters (which promote protein content) include cool conditions throughout phenological stage 4.2, hot temperatures throughout stages 4.3 to 5.2 and extreme temperatures in stage 5.4, accompanied by low precipitation from phenological stage 4.2 through 5.2.

These weather parameters referenced five (of the six) phenological stages (4.2 through 5.4), included seven temperature-related parameters and one precipitation-related parameter, and together accounted for 38.7% of the variation in final protein content. This significant environmental impact on protein is supported by Daun's (2006) study of western Canadian canola and by Pritchard et al. (2000). Some studies have even determined protein was more affected by environment than oil concentration (Sernyk and Stefansson 1982; Gunasekera et al. 2006b), although this may be due to the successful oil breeding programs creating robust canola varieties.

Although many studies investigating the effects of temperature on protein content focus on the positive (in reference to an increase, not to its desirability from a quality standpoint) relationship between high temperatures and protein, the model in the current study selected two weather parameters (B_CD<8 and -B_SDD>31) which describe the positive effect of cool temperatures on protein content. However, many studies concentrate on the effect of temperature throughout seed development (Canvin 1965; Aksouh et al. 2001; Aksouh-Harradj et al. 2006), whereas the current study selected parameters describing cool temperatures before seed development, throughout the flowering stage (phenological stage 4.2). In a related study, Bahrani and McVetty (2007) observed that canola grown in a field setting under cooler, moister conditions produced significantly higher final protein content than those in grown in warmer, drier conditions in a greenhouse. The selection pressure (seleting for preferred genotypes) applied to greenhouse grown (F_3) canola did influence the protein content of the next generation of (F_4) canola planted in the field, but the greater protein values were also attributed to the cool, moist environment in the field (as opposed to the greenhouse environment that the F_3 generation grew under). It was concluded that these conditions allowed for maximum phenotypic expression of protein content, along with other quality parameters (i.e. oil content). Further support for this theory comes from the selection of the temperature 31^{o}C for the parameter -B_SDD>31. This value is very similar to the maximum value across the range of preferred temperatures for plant growth (30^{o}C), as shown in the Canola Grower's manual (Thomas 1995), and daily maximum temperatures above 30^{o}C were determined to have the strongest correlation with yield (another phenotypic expression of the genotype) in another study (Kutcher et al. 2010).

The selection of B_CD<8 (cold stress day) rather than B_CDD<8 (cold stress degree day) highlights the importance of the duration rather than the intensity of low temperatures throughout phenological stage 4.2. This duration referred to was fairly significant, as the individual sample values for this parameter ranged from 0 to 10 (inclusively), while the phenological stage generally only lasted 10 to 15 days.

Alternatively, the selection of parameter -B_SDD>31 highlighted the impact of intensity of temperatures rather than duration. Although Angadi et al. (2000) did not quantify the effects on protein, their study did determined that short periods of intense heat stress at the early flower stage had much more of an effect on various physiological qualities (shoot dry matter, seed yield, harvest index, fertile pods per main stem, seeds per pod and seed weight) than both the same intensity of stress applied later in development and less intense heat stress at the same stage.

While cool temperatures had a positive effect on protein content during the flowering stage (according to the protein model), warm temperatures had a positive effect on protein content when applied later in development. The importance of the timing of temperatures was also noted by Morrison (1993), who found that heat or cold stress could have opposite effects on seed fertility, seed weight and number of seeds per pod depending on whether it was applied from seeding until the vegetative stage or the late flower stage. This study also determined that shifting from cold to hot conditions was often harder on the plant than moving it from hot to cold conditions, and that the stage most sensitive to heat stress was from late bud to seed development (equivalent to phenological stage 4.3 through 5.2).

Elevated protein content has often been linked to plant heat stress (Canvin 1965; Pritchard et al. 2000; Aksouh et al. 2001; Gunasekera et al. 2006b) which has been shown to promote flowering and hasten maturity (Aksouh-Harradj et al. 2006).

Canvin (1965) observed rapeseed grown under progressively lower temperatures generally took an increasing number of days to proceed from fertilization to maturity. Several years later, in a study with the first hybrid plants, little correlation between days to flowering or days to maturity and protein content was observed, although possible advances in hybrid breeding could have been a factor (Sernyk and Stefansson 1982). The results of the current study suggest the effect of heat on protein content is specific to the flowering and seed development stages, and not the entire growing period.

The timing of heat treatment was also crucial in studies by Aksouh et al. (2001) and Aksouh-Harradj et al. (2006), who determined that plants subject to heat stress earlier in development (from 20 to 30 DAF, equivalent to stage 4.4) had a less significant reaction to the heat stress than plants stressed at a later stage in development (from 29 to 36 DAF, equivalent to late phenological stage 4.4 or early stage 5.2), despite a greater duration of heat treatment. Understandably, partial credit for this disparity in results may be due to the difference in temperature regimes, including a difference in minimum (night) temperatures (23^{o}C versus 21^{o}C) (Aksouh et al. 2001; Aksouh-Harradj et al. 2006). These findings also suggest that an acclimatization period before intense temperatures can negate (or diminish) an expected reaction. At high temperatures, enzymes and reaction rates can increase, but with extreme temperatures, especially without an acclimatizing period, the reactions can slow down or stop.

The sensitivity of the plant to heat stress during phenological stages 4.3 through 5.2 may have to do with all the biochemical processes and physiological changes occurring throughout seed development. Seed weight dramatically increased from approximately 7 DAP to 40 DAP (equivalent to phenological stages 4.3 through

5.2) (Fowler and Downey 1970) and accumulated photosynthates are converted to preferred material for energy storage (Thomas et al. 2003) including oil and protein. Throughout this time there is also a shift in deposition of total dry weight, with less emphasis put on leaves and more emphasis put on stem, then pod, then seed weight accumulation (Thomas 1995).

In a study which used calendar days rather than heat units, July maximum temperatures (equivalent to phenological stages 4.2 to 4.3 or early stage 4.4, depending on the seeding date) were the most consistently and significantly correlated factor to oil-free protein in western Canadian canola (Daun 2006). In addition, Gunasekera et al. (2006b) reported that average maximum post-anthesis temperatures had a significant ($P<0.001$) effect on protein concentration. Contrary to the findings in the current study, Daun (2006) also noted some importance of June maximum temperatures (approximately equivalent to early stage 3.2) on protein content and Gunasekera et al. (2006b) reported average maximum pre-anthesis temperatures had a significant ($P<0.001$) effect on protein concentration.

The three weather parameters describing the positive impact of high temperatures on protein content throughout phenological stages 4.3 through 5.2 were CD_MaxT, D_SD>25 and -E_CD<14. This trend is not surprising, as maximum (Daun 2006) and moderately high temperatures have been associated with increased protein values in past studies (Canvin 1965; Pritchard et al. 2000; Aksouh et al. 2001; Gunasekera et al. 2006b; DeClercq 2008).

The effects of high temperatures on protein values are obvious when comparing climates. Australian field studies which take place under higher mean and maximum temperatures which have much greater protein values (Si et al. 2003; Gunasekera et al. 2006b) than those carried out under cooler Canadian conditions

(Hickling 2005; May et al. 2010). Regardless of the country measured, temperatures throughout phenological stages 4.3 through 5.2 (which correspond to July and August in Canada) are usually fairly high because of the time of the growing season. Therefore, the selection of a 25^{o}C threshold is more appropriate throughout stages 4.3 through 5.2 (than other stages) because there are more occurrences of these values (based on average temperatures occurring throughout the calendar days which correspond to these growth stages).

The selection of the 25^{o}C threshold is also close to the 26/18^{o}C temperature regime which produced higher protein content than those grown at 18/10^{o}C (Triboi-Blondel and Renard 1999) and the 26.5^{o}C temperature which produced the highest protein content in Canvin (1965). On the contrary, Aksouh-Harradj et al. (2006) found that there was no significant difference in protein content between canola grown under 22^{o}C or 28^{o}C throughout the equivalent of phenological stage 4.4.

Throughout phenological stages 4.3 to 5.2 the duration of high temperatures and length of time without cold temperatures was emphasized over the intensity of temperatures by the parameters selected in the protein model (D_SD>25 and -E_CD<14). Similar conclusions could be made from May et al. (2010), in which the duration of the flowering period was more associated with protein content than the day on which flowering began, and higher protein values were linked to shorter flowering periods. Gunasekera (2006b) also found that post-anthesis period had a significant ($P<0.001$) effect on protein concentration. The length of growth stages may be even more critical in a region such as western Canada, where the length of the growing season is already limited (Bullock et al. 2010).

Aside from the impact of duration, the importance of heat intensity throughout seed development was also suggested by the inclusion of the parameter CD_MaxT.

The greater impact of heat intensity over heat duration was concluded in two studies where extreme temperatures over a shorter duration ($38^oC/28^oC/23^oC$ for 5/9/10 hours over 4 days and $40^oC/21^oC$ for 4/20 hours over 7 days) had more of an impact on protein content than a moderate heat stresses over an equal or longer duration ($28^oC/23^oC$ for 14/10 hours over nine days and a 5^oC stepped increase from 21^oC to 40^oC balanced over seven days). This was despite a greater number of plant heat units (GDD) accumulating over the course of both moderate treatments (57 GDD versus 35 GDD and 45DD compared to 15 DD) (Aksouh et al. 2001; Aksouh-Harradj et al. 2006).

The model also selected temperature extremes (both low and high) throughout phenological stage 5.4 for contributing to higher protein content. There are very few studies which investigate the effects of temperature on canola quality this late into the growing season because oil production tapers off to a minimal amount after 35 DAP (Fowler and Downey 1970) or past 800 degree days (Baux et al. 2008), which is roughly equivalent to the late phenological stage E, early stage F. In addition, locations that regularly experience heat stress late in the growing season may swath their crops before they reach this stage phenological stage 5.4, to avoid any seed damage or shatter losses. Finally, many plants that reach phenological stage 5.4 are close to being swathed or straight-cut that a significant effect of any weather parameters on seed quality may not be expected. However, the plants are not completely mature at the beginning of this stage, thus temperature stress which may shorten the duration of phenological stage 5.4 could impact protein content. For instance, Gunasekera et al. (2006b) found that the post-anthesis period had a significant effect on protein concentration and Canvin (1965) reported higher protein

contents in treatments with shorter fertilization to maturity periods and higher temperatures.

Since both weather parameters selected for phenological stage 5.4 (F_CDD<5 and F_SDD>31) describe temperatures outside of (above or below) the optimal growing temperature range (Thomas 1995) they can cause stress to canola, (Morrison 1993) which can hasten crop maturity (Thomas 1995) and increase protein content (Pritchard et al. 2000).

The only precipitation-related parameter selected by the model was the negative impact of accumulated precipitation from phenological stage 4.2 through 5.2 (-BE_SumPrecip). Gunasekera et al. (2006b) also found total rainfall and post-anthesis rainfall was negatively correlated with protein (r^2=-0.69). These results may be partially due to protein production opposing oil production, and partially due to moisture stress compounding the impact of high temperatures (which commonly occur at a greater frequency and intensity throughout the days corresponding to phenological stage 4.2 through 5.2).

The combination of a lack of precipitation and declining soil moisture from growing season evapotranspiration results in moisture stress, which limits the opening of the stomata for transpiration as a method of cooling, thereby increasing the magnitude of stress on the plant (Taiz and Zeiger 2006). This is especially critical when it occurs over the course of physiological growth (stage 4.2 through early 5.2) when moisture is still needed for production of plant material and oil content.

Another factor related to both available soil moisture, daily temperature values and final protein content is the soil nitrogen (N) levels. Critical for growth and development, a deficiency in N can result in reduced yields, yellowing and thin stems, while excess N can lead to green seed problems. Canvin (1965) hypothesized that

warm temperatures elevated the availability of N in the soil, which led to greater absorption of the nutrient, subsequent competition for carbon skeletons and even the diversion of carbon toward protein production rather than oil production.

Under moderate moisture levels adequate movement of the nutrient allows for sufficient plant uptake, which has been shown to increase plant yield (Gan et al 2007; May et al. 2010), height, kernel weight, water use, oil content (May et al. 2010) and protein content (May et al. 2010; MAFRI 2013b). However, N applications under excess moisture can lead to leaching, and N applications under dry conditions can lead to restricted yield potential but increased protein levels (MAFRI 2013b).

Supplemental N fertilizer applications have also been shown to affect the first day of flowering (Gan et al. 2007; May et al. 2010) and prolong the onset of flowering and maturity (Brandt et al. 2007), but only have a minor (and insignificant) effect on the total time to maturity (Gan et al. 2007), and no effect on flowering period (May et al. 2010).

Along with proper N applications, sulfur (S) amendments are also necessary for canola production, because of their joint role on protein synthesis-including amino acids cysteine and methionine (Grant and Bailey 1993). If S deficiencies occur along with high N applications yield can be severely decreased, in several soil types (Grant and Bailey 1993), which could explain the addition of S and B fertilizer to Gray Luvisolic soils of northeastern Saskatchewan improving the poor seed set and enhancing yields (through enhanced pod development) (Nuttall et al. 1987).

3.5.2.3 Chlorophyll Content. Like all higher plants, canola contains light-absorbing pigments called chlorophyll which are present in chloroplasts and assist in photosynthesis (Taiz and Zeiger 2006). During the reproductive stage, the seed grows develops and begins photosynthesizing in the embryo. Along with the production of

oxygen and activity of reduction molecules throughout seed development is the production and eventual degradation of chlorophyll content in the seed embryo (Eastmond et al. 1996). In optimal conditions this process occurs over approximately 15 to 42 DAF and generally follows the pattern of accumulation and reduction of fresh seed weight (Rakow and McGregor 1975). More specifically, chlorophyll content (within the seed) increases fairly rapidly from 15 to 32 DAF (equivalent to phenological stages 4.3 through 4.4), where it peaks, and then follows a sharp decline from 32 to 42 DAF (equivalent to phenological stages 4.4 through 5.2) where it remains at a minimal level (< 0.5 µg/seed) (Rakow and McGregor 1975).

While the peak amount of chlorophyll is similar across cultivars (Rakow and McGregor 1975; Ward et al. 1992; Ward et al. 1995), the amount and rate at which chlorophyll degradation occurs can be altered by several factors, including the seed moisture content and temperature throughout the degradation period, length of growing season, seeding date and harvest method (Rakow and McGregor 1975; Ward et al. 1992; Ward et al. 1995; Thomas 1995) and possibly by ethylene content (Ward et al. 1995). In order to achieve low final chlorophyll values, these factors must align to create a moderate degradation rate over a sufficient duration. The convergence of these factors is especially critical since the length of chlorophyll processes are somewhat inelastic, as inferred from the similarity in durations of chlorophyll production and degradation between dissimilar varieties (Rakow and McGregor 1975). As well, unfavourable conditions have been shown to lead to high chlorophyll values (Appelqvist 1971).

The chlorophyll model explained 6.6% of the variation across values with six weather parameters related to low temperatures or the available moisture balance. Interestingly, the intercept value was a negative value, and the parameters had a

positive impact on the quality parameter. In terms of canola grading, chlorophyll is an undesirable characteristic which indirectly has a negative impact on canola quality (CGC 2012). Although not always measured, chlorophyll has a strong relationship with green seeds (r^2=0.949), which allows for a quick measurement of this substitute (distinctly green seeds) as a degrading factor (Daun 2003).

While the mean chlorophyll value of 10.92 for the 2008&2009All dataset of canola, No.1 Canada is fairly low compared to both the 2007 crop year for canola, No.1 Canada and the previous 10 year-average for canola, No.1 Canada (DeClercq 2008), the variance was huge at 28.81, producing the largest standard deviation (5.37) across all quality parameters measured (Appendix 3). This large range in chlorophyll values may be related to the model accounting for the lowest amount of variation of all quality parameter models.

Earlier research states chlorophyll content in canola is highly weather dependent (Daun 2006), and may have been some of the cause behind the huge range in chlorophyll values, which was not abnormal for the parameter across western Canadian canola (Daun 2003). The model identified parameters that could be divided into two themes: the positive relationship with moisture and the positive relationship with minimum temperatures. Across both of these themes the impact of phenological stages 4.2 and 4.4 through 5.4 dominated, with an emphasis on the duration of the weather conditions over the intensity of the conditions. Stages 4.3 through 4.4 correspond to beginning of chlorophyll production in the seed, while stages 5.2 through 5.4 correspond to regular chlorophyll degradation (Rakow and McGregor 1975; Eastmond et al. 1996).

Among the top two ranking parameters selected for the chlorophyll model were the positive impacts of the summation of the water stress indices measured

across stages 4.2 through 4.4 and measured across stages 4.4 through 5.4. These two parameters, along with the positive impact of the precipitation summation throughout stage 4.4 (on chlorophyll content), are indicative of the positive impact moisture has on chlorophyll content. DeClercq (2008) also determined that wet years were associated with higher and dry years were associated with lower chlorophyll content in western Canadian canola crops. Similarly, Daun (2006) also found that August (approximately equivalent to stage 4.4 or 5.2) precipitation had a significant effect on final chlorophyll content of western Canadian canola crops.

The reason for the effect of precipitation on chlorophyll content is likely due to its ability to delay maturation. Higher precipitation prolongs the flowering duration, which delays the beginning of maturation until later in the season and can further result in one of two scenarios. The reduced amount of time before the end of the growing season (marked by the first frost) can limit time for chlorophyll degradation to occur. Delayed maturation can also force the chlorophyll degradation to occur under cooler temperatures (which are characteristic of autumn), which slows the rate of chlorophyll degradation and leaving a higher content at harvest (Ward et al. 1992), similar to the impact of late maturing varieties (Ward et al. 1992; Daun 2003) or late seeding dates (Ward et al. 1992). Seed moisture content has been shown to decrease along a similar time scale to chlorophyll degradation, but the seed moisture content was not determined to directly cause this (Ward et al. 1995).

Contrary (to the current study), it has been hypothesized that chlorophyll degrading enzymes may be dependent on moisture levels, since higher moisture content is associated with more rapid chlorophyll degradation (Ward et al. 1995).

In some cases, delayed harvest (limiting the amount of time before the nocturnal temperatures begin approach the freezing mark) may leave producers with

fewer days to select from for swathing or harvesting and forces some (producers) to swath canola during undesirable conditions, such as hot temperatures, which often result in high chlorophyll contents (Ward et al. 1992; Daun 2006; DeClercq 2008).

The phenological stages identified for the impact of moisture on chlorophyll content support the hypothesis of the impact on delayed harvest. Although together the two WSI parameters select for the entire reproductive stage, which includes the time leading up to and including maturation, the stage common to both WSI parameters and the precipitation parameter is 4.4, when flowering is completed. The increased moisture throughout this period would delay the onset of maturation, which includes the beginning of the desiccation.

The other trend that emerged from the parameters selected for the chlorophyll model was the positive impact of minimum temperatures, both at the early reproductive stages and into early maturation. These findings are supported by Daun (2006), who found that lower minimum temperature in June and September impacted chlorophyll content (which are generally correspond to phenological stage 3.2 or 4.2 and 5.2 or 5.4, respectively). DeClercq (2008) also reported higher chlorophyll contents in cool growing seasons for western Canadian canola crops. While the lower temperatures at the beginning of the reproductive stages can delay the onset of maturity (and therefore chlorophyll degradation), minimum temperatures throughout stage 5.2, which correspond to the time for regular chlorophyll degradation (Rakow and McGregor 1975) and can slow chlorophyll degradation to an insufficient rate (Ward et al. 1992) (which will require more time to diminish than there may be left in the growing season). This could be critical for chlorophyll, which has somewhat of an inelastic total developmental time (Rakow and McGregor 1975).

The required time to complete plant maturity (including chlorophyll production and degradation) (Ward et al. 1992; Ward et al. 1995) is especially critical with *Brassica napus* canola, which has an indeterminate flowering pattern and the slightly longer growing season of the *Brassica rapa* canola that was previously grown (Daun 2003). In addition, the late seeding dates of the samples in the current study, along with the short Canadian growing season underline the need for sufficient time during maturation. Delaying the maturation period also increases the chance of frost occuring prior to maturity which can fix chlorophyll content and prevent its degradation (Thomas 1995).

The reason for the extremely low predicting power of the chlorophyll model is likely related to the impact of weather conditions at the time of swathing or harvesting not being accounted for (since this activity ended the accumulation of P-Days). A rapid loss of moisture can result in fixed chlorophyll content. This can occur when fields are swathed under hot, dry conditions (Ward et al. 1992; Thomas 1995) or canola is dried down too quickly in a drying room or bin (Ward et al. 1992). Unfortunately, when the crop is swathed or harvested, the P-Days stopped accumulating and if the phenological stage was not completed, the weather parameter being measured is incomplete and left as a missing value. Therefore, the strong impact of weather conditions at swathing or shortly after (generally during phenological stage 5.2 or 5.4) were not considered for this study and may be a huge contributor to the reason the predicting power of the chlorophyll model was so low. In addition, most of the samples in this study that were swathed did not reach phenological stage 5.4, while those that were straight-cut likely accounted for most of the samples which reached and provided values for weather parameters measured for phenological stage 5.4.

Above all, regardless of environment having a significant influence on final chlorophyll values (Ward et al. 1995), a certain level of background chlorophyll always exists (Daun 2003), even under ideal conditions.

3.5.2.4 Glucosinolates Content. Similar to chlorophyll, glucosinolates are detrimental to the quality of canola (Downey and Craig 1969), so lower content is desirable. When exposed to water and myronase enzymes, glucosinolates produce N and S-containing organic compounds (CIGI 1993) which can act as anti-growth factors and cause health problems in livestock (Bell et al. 1972), and have negative impacts on oil processing (CIGI 1993) and soil microorganisms (Brown and Morra 2005). Unlike chlorophyll, the allowable quantity of glucosinolates (which has decreased over the years) is stated in the definition of canola (CCC 2011b). Therefore, the considerable decline of total content over the years has resulted in higher quality canola (Daun 1986; Barthet 2009). This progress may be the reason genotype has been shown to have a greater impact on final glucosinolates values than environment in several studies (Mailer 1989; Mailer and Pratley 1989; Pritchard et al. 2000). This is further supported by the findings of Kondra and Steffanson (1970) and Friedt and Luhs (1998) who claimed glucosinolates concentration is controlled by three dominant-recessive genes and has high heritability.

The five model-selected parameters that together accounted for 43.5% of the variation in glucosinolates values were all derived from temperature rather than precipitation. This contradicts Mailer and Pratley (1989), who determined a strong correlation between glucosinolate content and water availability, in addition to evapotranspiration from anthesis to maturity. An explanation for this discrepancy may lie within the (finite) positive relationship between soil moisture, S and N availability, which has been shown to increase glucosinolates content (Jan et al. 2010).

Uptake of some soil nutrients, including S, is dependent on moisture for translocation and has been shown to effect glucosinolates content (Mailer and Pratley 1990), thereby linking higher soil moisture to greater movement of nutrients and increased plant uptake (MAFRI 2013b). Furthermore, increased nutrient uptake can also lead to increased yields, which have been positively (Daun 2006) and negatively correlated (Aksouh et al. 2001) with glucosinolates. In addition, water availability has even been shown to affect glucosinolate content in conjunction with boron content. Price et al. (1998) discovered that at low boron availability, water stress increased glucosinolates content, but under water-stressed conditions, high boron availability produced lower glucosinolates content.

The parameters that were selected by the glucosinolates model can be grouped under two different trends. The parameters –CD_AveT and -B_SDD>31 are indicative of the negative impact high temperatures during the early to mid-reproductive stage have on glucosinolates content. Meanwhile, the inclusion of parameters CD_SDD>22, F_SD>22Cum, and -BF_CDD<17 describe a positive effect of high temperatures (both in terms of duration and intensity) throughout the total plant development, especially throughout the latter part of the reproductive stage.

The negative impact of high temperatures was characterized by the increased average temperatures throughout phenological stages 4.3 through 4.4 (-CD_AveT) and increased number of stress degree days with a 31^{o}C threshold, throughout phenological stage 4.2 (-B_SDD>31), highlighting the temperature impact on growth and development, rather than the senescence or growing season length. Actually, high temperatures causing heat stress can affect glucosinolates content through indirect effects on the growth of canola roots, which do not reach 85% of their maximum length until peak flowering, during phenological stage 4.3. Hence, heat stress to the

plant could stunt root growth, which would prevent adsorption of deep or leached sulphur, resulting in a S deficiency, which has been associated with low glucosinolates content (Nuttall et al. 1987; Mailer 1989; Jan et al. 2010).

Heat stress earlier in the growing season (ex. during phenological stage 4.2) can also result in the flowering duration being shortened (May et al. 2010) and even late seeded canola ripening before reaching the desiccation stage when hot, dry conditions could otherwise induce higher glucosinolates and drastically reduce crop yields (Angadi et al. 2000). Therefore by avoiding this temperature stress, the final glucosinolates content would be lower. In support of this, Sang et al. (1984) hypothesized that increased glucosinolates contents that resulted from late seeding were actually linked to increased temperatures that the crop endured at an early physiological stage.

The parameter (-CD_AveT) suggests lower average temperatures throughout phenological stages 4.3 through 4.4 produce greater glucosinolates content. This refers to the times when pods, stems and seeds are forming (Thomas 1995) and total dry weight is at a peak (Thomas 1995), in addition to oil production (Fowler and Downey 1970). The positive relationship between glucosinolates content and oil production has been determined at a slightly later growth stage in earlier canola cultivars (Kaur et al. 1990) and is demonstrated in the current study by the inclusion of parameters describing a positive relationship with low temperatures throughout stage 4.3 in each model (-CD_AveT and BD_CD<11 in glucosinolates and oil models, respectively). Regardless, cool temperatures encourage greater phenotypic expression of the plant genotypes.

The selection of the parameter -CD_AveT for the glucosinolates model means the actual temperature that is being selected for is unknown. For example, if the

average temperature throughout this period was relatively low, at 18°C (resulting from an 11°C to 25°C range in temperatures), some of the below average temperatures (ex. 11°C) that were dragging the mean down (to the value of 18°C) could have actually caused stress and increased the glucosinolates content, resulting in a negative relationship. Furthermore, if the higher temperatures (ex. 25°C) were not actually causing stress to the plant, they may not have decreased the total glucosinolates values and therefore would still result in a negative relationship.

The cooler temperatures throughout these growth stages can also result in reduced evaporation, which can allow for greater soil moisture. It has been suggested that greater soil moisture levels may allow for greater S translocation (Mailer 1989; Mailer and Pratley 1990), which can result in increased glucosinolates content (Kaur et al. 1990).

The other trend amongst the selected weather parameters was the positive impact of heat on glucosinolates content. More specifically, the greater number of days throughout phenological stages 4.3 and 4.4 with increasingly higher temperatures above 22°C (CD_SDD>22) and the greater number of days from seeding until the end of phenological stage 5.4 with temperatures above 22°C (F_SD>22Cum) resulted in higher glucosinolates content. Greater final glucosinolates content was also associated with fewer cold degree days (at base temperature 17°C) throughout phenological stages 4.2 through 5.4 (BF_CDD<17). This positive relationship between heat and glucosinolates content is supported by several Australian studies (Aksouh et al. 2001; Aksouh-Harradj et al. 2006; Bahrani and McVetty 2007). In fact, Aksouh et al. (2001) found that short bursts of extremely hot temperatures (40°C) from 25 to 29 DAF (which roughly corresponds to phenological stage 4.4 or 5.2) produced canola oil with significantly higher glucosinolates than both the control

(21°C/16°C day/night), and the treatment with a progressive increase in temperatures, across three varieties. Understandably, this increase was partly attributed to the less negative impact heat had on glucosinolates, relative to other seed components (such as oil), which make up the rest of the grams of seed measurement in µmol/g (that glucosinolates are measured in).

Still, another controlled study by Aksouh-Harradj et al. (2006) which looked at the effect of moderate and extreme heat increases found that only two out of three varieties of canola showed increases in glucosinolate values (from seeds on the main stem) for moderate or extreme temperature increases and these increases were not significant. However, this may be the result of the timing of the treatments, as the moderate heat treatment occurred from 20 to 29 DAF and the extreme heat treatment took place from 25 to 29 DAF (both approximately equivalent to growth stage 4.4), when the model (in the current study) selected two opposing temperature parameters (increasing and decreasing impacts of heat). The reason for this discrepancy may be linked to the finding the Aksouh-Harradj et al. (2006) study, which is that there was a significant difference between genotypes in this study. Another hypothesis is that the controlled environment of this study buffers the field setting effects of increased heat on canola plants (such as increased evapotranspiration causing reduced moisture and additional stress to the plant), since plants in the experiment were "watered twice daily to ensure adequate soil moisture" (Aksouh-Harradj et al. 2006).

Elevated temperatures for the duration of the entire growing season (an average difference of 5.6°C) had the same positive impact on glucosinolates as in another study without any extreme stress-inducing heat (in opposition to the previously mentioned study), showing that high temperatures had a positive effect on

glucosinolates from more than just reducing other seed components (Bahrani and McVetty 2007).

Daun (1986) found (from crop surveys) that canola grown in northern Alberta, where longer growing season days prevail (and therefore potential impacts of a greater duration of heat) always had higher glucosinolates values than central or southern Alberta, which generally has higher average and maximum temperatures (but shorter daylight hours) over the course of the growing season (AAFC 2010). Alternatively, Pritchard et al. (2000) determined that neither average nor minimum temperatures had a significant effect on glucosinolates content in Australian crops. However, this could be due to the relatively high average and minimum temperatures in Australia, compared to the very low minimum temperatures in Canada that need to be avoided in order to produce high glucosinolates content.

3.5.2.5 Fatty Acid Profile. The majority of weather variables selected by the model for predicting the content of fatty acids were measures of temperature. Precipitation variables were also selected, primarily throughout phenological stage 5.2 (-E_SumPrecip, E_WSISumCum, B_WSISumCum and E_WSISum). The impact of temperature on fatty acid synthesis has been validated by several other studies (Canvin 1965; Trémolières et al.1982; Deng and Scarth 1998; Daun 2006). The imbalance of precipitation variables selected could be a symptom of the Canadian conditions, where more moderate temperatures minimize the impact of moisture stress noted in other warmer climates such as Australia. There is also a possibility that temperature-related parameters were the best predictors of canola quality parameters because temperature data is much more accurate (across the western Canadian prairies) than precipitation data.

There are a few processes that could be affected by the temperature. Higher growing season temperatures increase the number of heat units accumulated over a shorter duration, reducing the number of days required until maturity, and therefore allowing less time for oil production, which can result in lower oil content (Yaniv et al. 1995). Higher growing season temperatures also favour the production of protein over oil and hinder the desaturation process, often resulting in lower unsaturated fatty acid and higher saturated fatty acid content (Canvin 1965). While temperature appears to have a greater influence on fatty acid production than precipitation (Pritchard et al. 2000), the moisture balance that results from precipitation and evapotranspiration have been shown to affect fatty acid content as well.

The production of several individual fatty acids results from a series of biochemical reactions primarily using the acetyl-CoA carboxylase and fatty acid synthase that initially creates saturated fatty acids. In canola the primary saturated fatty acids produced are palmitate and stearate, which then react with elongases (especially palmitate) and desaturases to produce increasingly unsaturated fatty acids (with progressively more double bonds) (Harwood 2010). By this sequence of events palmitate and stearate act as precursors to unsaturated fatty acids oleic , linoleic and linolenic acid (Stumpf 1972; Harwood 2010). Since the desaturases (desaturation enzymes) are critical to the production of the unsaturated fatty acids, the effect of temperature on these enzymes affects the quantity of individual fatty acids produced. Under extremely high temperatures, these enzymes may even become deactivated (Canvin 1965; Stumpf 1972). The activity of oleic and linoleic desaturation enzymes, specifically, have been shown to be decreased by high temperatures (Aksouh-Harradj et al. 2006). Deng and Scarth (1998) proposed that high temperatures may have a

similar effect on canola as on soybeans: through stimulating the production of oleic acid and inhibiting the desaturation sequence.

A more in-depth look at the relationships between the production of individual fatty acid recognized positive relationships between total oil and oleic acid content as well as linoleic and linolenic acid, but negative relationships between oil and linoleic, oil and linolenic acid, oleic and linoleic, and oleic and linolenic content (Stefansson and Storgaard 1969; McCartney et al. 2004). These trends were echoed in the current study, except for a weak negative relationship between linoleic and linolenic acid (rather than the positive one in Stefansson and Storgaard 1969), which may be attributed to current varieties catering to a demand for lower linolenic acid. Since the oleic fatty acids make up such a large portion of the total fatty acid content, environmental factors at any stage in crop development that affect oleic concentration, will also affect total oil content.

The physiology of canola and necessary steps of fatty acid production and desaturation, along with the timing of the plant vulnerability (related to these processes) seems to drive the phenological stage at which the weather parameters have the most impact on oil quality parameters. The model results emphasized a pattern where progressively more unsaturated fatty acid (greater number of double bonds) were affected by weather occurring throughout progressively later (corresponding) growth stages. Saturated fatty acids appeared to be most affected by weather parameters measured throughout phenological stages 3.2 and 4.2, while parameters for the oleic, linoleic, linolenic acid models were mostly measured across stages 4.3 through 5.4 and the parameters for the iodine value model heavily focussed on the late growth stages (with stage 5.2 dominating the weather parameters).

Reference evapotranspiration (ETo) and standard evapotranspiration (ETc) or crop water demand were also found to affect the final content of individual fatty acids. Evapotranspiration (ET) is the rate (mm/day) at which moisture is lost, through the combination of evaporation and transpiration, from a standardized cropped surface. It is a function of incoming solar radiation (which depends on latitude and Julian day) as well as the maximum, minimum and mean daily temperatures. In addition, the WSI parameter was also selected, which considers not only moisture demand (i.e. ET), but also moisture supply through precipitation. Across the fatty acid profile, an ET parameter was selected for all fatty acid quality measures except linoleic acid. More specifically, C_EToSum was selected for oleic acid, A_EToSum was selected for both linolenic acid and iodine value models, -A_EToSum was selected for the saturated fatty acids model. In these cases, greater evapotranspiration quantities were correlated with greater unsaturated fatty acid content (oleic acid, linolenic acid and iodine value), lower saturated fatty acids content.

Some of the relationships and correlations amongst fatty acids and total oil content may have also impacted some of the parameters selected in various fatty acid models. For example, oleic acid is strongly tied to total oil content (because it accounts for a huge percentage of total oil), only one double bond away from saturated fatty acids (and therefore more influenced by saturated fatty acids than unsaturated fatty acids with several double bonds). In addition, linoleic acid acts as an intermediary between oleic and linolenic acid (along the desaturation progression), but as an unsaturated fatty acid, plays an important role in final iodine value (and therefore plays a part in the weather parameters that are selected in the iodine value model). Meanwhile, the iodine value (a measure of unsaturation) would be expected to have a negative relationship with saturated fatty acids and therefore weather

parameters that promote iodine values would be expected to reduce the production of saturated fatty acids, as well as oleic acid (a mono-unsaturated fatty acid) to a lesser degree.

3.5.2.6 Oleic Acid Content. The oleic acid model contained eight weather parameters which collectively explained 23.5% of the variation in content (slightly above the other individual unsaturated fatty acid models). Oleic acid makes up the majority of total fatty acids, with an aggregated mean of 62.7%. Although still acceptable, oleic acid samples values had the greatest range, variance and standard deviation of all individual fatty acids examined. With only one double bond separating this mono-unsaturated fatty acid from a saturated fatty acid, it has the lowest degree of unsaturation of the unsaturated fatty acids tested in this study. Despite a significant effect of variety and germplasm on saturated fatty acid values, and breeding efforts to maintain uniform fatty acid composition across environments, oleic acid has been found to be responsive to its environment, with significant effects of environment (Pritchard et al. 2000) and temperature (Deng and Scarth 1998; Aksouh-Harradj et al. 2006).

As referred to earlier, the temperature impacts on oleic acid production are due to two (opposing) factors. The cool, wet conditions favour oil production, while high temperatures favour the shift toward saturation (and oleic acid) and away from highly unsaturated fatty acids (such as linoleic and linolenic acid). Noting these themes, three trend emerged for the selected model parameters, including the positive impact of cool temperatures during flowering (phenological stages 4.3 and 4.4) (C_CD<17, -C_SD>25 and -D_SDD>31), the mainly positive effect of hot and dry conditions during seed development and maturation (C_EToSum, -E_SumPrecip, F_SD>28Cum,

-F_CDD<5, -F_SD>19) and the specific impact of evapotranspiration and precipitation (C_EToSum and -E_SumPrecip).

The phenological stages most frequently reference in the selected weather parameters were 4.3 and 5.4. This selection may be due to the majority of oleic acid production occurring between 14 and 21 DAP (Fowler and Downey 1970), which roughly corresponds with stage 4.3. Up until phenological stage 5.4 oleic acid production follows a fairly consistent production curve, but throughout stage 5.4 the change in content is more variable (increase, remain or decrease) depending on the variety being grown and growing conditions (Perry and Harwood 1993; Deng and Scarth 1998).

As a large contributor to total oil content, greater oleic acid content can result from being grown under temperatures within the optimal temperature range (Thomas 1995) throughout phenological stages 4.3 and 4.4 (Canvin 1965; Deng and Scarth, 1994; Yaniv et al. 1995), which is in line with the increased the number of days throughout stage 4.3 with temperatures below 17°C (C_CD<17) producing higher oleic acid content in the current study. It also supports the negative impact of increased number of days in stage 4.3 with temperatures above 25°C (-C_SD>25) and an increased number of degree days throughout stage 4.4 with temperatures above 31°C (-D_SDD>31) being associated with lower oleic acid content in this study. It has been shown that canola exposed to very low temperatures (12°C) at the equivalent to phenological stage 4.4 produced higher oleic acid levels than a moderate temperature (17^{o}C) (Trémolières et al. 1978). This effect was drastically reduced when the low temperatures were applied later in the growing season, at approximately phenological stage 5.4 (Trémolières et al. 1978).

Alternatively, the production of oleic acid as the least unsaturated of all the unsaturated fatty acids considered favours growth under warm conditions. This was exemplified by the positive relationship between the number of stress days above 28^{o}C from seeding until the end of stage 5.4 (F_SD>28Cum) and was explained by Canvin (1965) as the reflection of the decreased desaturase enzyme activity under very warm conditions (resulting in less production of polyunsaturated fatty acids). In addition, the lower number of cold (stress) degree days below 5^{o}C throughout phenological stage 5.4 (-F_CDD<5) was related to higher oleic acid content, with greater amounts of cold stress degree days associated with depressed oleic acid content.

Along the same trend, the negative relationship between oleic acid content and the number of stress days throughout stage 5.4 above the 19^{o}C threshold (-F_SD>19) represents the detrimental effects of moderate temperatures on oleic acid content. This was also determined by Deng and Scarth (1998), who found that oleic acid content was lower in the moderate 25^{o}C/20^{o}C regime than either the cool (15^{o}C/10^{o}C) or hot (30^{o}C/25^{o}C) temperature regimes. These low values were attributed to the promotion of desaturase enzyme activity and the resultant conversion of oleic acid to more unsaturated fatty acids (linoleic and linolenic acid).

On a related note, the model selection proposed that the summation of a reference evapotranspiration parameter throughout phenological stage 4.3 (over which the most rapid oleic acid synthesis occurs) (C_EToSum) had a direct correlation with oleic acid content. Reference evapotranspiration (ETo) is a function of temperature, with higher temperatures favouring both greater ETo and increased oleic acid content. Furthermore, by the model selecting the summation version of the parameter, the importance of duration of the condition is emphasized.

The oleic acid model also included a parameter describing a negative relationship between oleic acid and the precipitation accumulation throughout phenological stage 5.2 (-E_SumPrecip), where higher precipitation throughout stage 5.2 was correlated with lower oleic acid content. Despite oil production generally being favored by cool, moist conditions, there may be several hypotheses as to why high rainfall late in development had a negative impact on oleic acid content. It may be due to an indirect buffering impact of precipitation on the temperatures, in which the warm temperatures that usually drive production of mono-unsaturated fatty acids (rather than poly-unsaturated fatty acids) is lessened by the moist conditions allowing increased plant transpiration (as a cooling mechanism) without moisture stress. Although there was slight (insignificant) negative impact of high precipitation on the samples in the canola quality data, there was no significant effect of precipitation.

3.5.2.7 Linoleic Acid Content. Linoleic acid is in an intermediary position along the desaturation progression (progression from saturated to unsaturated fatty acids) and thus its final content is affected by all the weather parameters which impact the production of the fatty acids preceding and following it (oleic and linolenic acid, respectively). There were only four weather parameters (E_WSISumCum, CE_MinT, B_WSISumCum, and CF_MinT) selected for the linoleic acid model.

The most frequent phenological stage represented within the weather parameters selected for the linoleic acid model was stage 5.2, followed by stage 4.3 and 4.4. Together the weather parameters were able to explain 22.1% of the variation in linoleic acid values, which is slightly less than the oleic acid model (23.5%) and very similar to the amount of variation the linolenic acid model (22.0%) could explain. This significant amount of variation which can be explained by weather parameters suggests that environment has a substantial impact on this fatty acid.

Results from Trémolières et al. (1978) and some cases in Yaniv et al. (1995) add support to this finding.

Two strong trends emerged from the weather parameters selected for this model, including the impact of water stress indices calculated over a long duration, and the positive impact of minimum temperatures throughout pod and seed development on final linoleic acid content.

As an unsaturated fatty acid linoleic acid, moderately low temperatures throughout seed development are often associated with greater linoleic values (Canvin 1965; Trémolières et al. 1978). However, some studies have reported that extremely low temperatures have also been determined to reduce linoleic acid content (Yaniv et al. 1995; Deng and Scarth 1998). The increase in linoleate desaturation activity (when converting oleic acid to linolenic acid via the linoleic acid intermediary) at low temperatures may be the reason for this (Trémolières et al. 1978). Furthermore, despite the bulk of linoleic acid production occurring between 14 to 35 DAF (equivalent to phenological stage 4.3 through 4.4) (Fowler and Downey 1970), the final alterations in linoleic acid content have been reported to vary over the course of phenological stage 5.2 and 5.4 (Deng and Scarth 1998).

In another study, Baux et al. (2008) determined that the sum of minimal temperatures during the equivalent of phenological stage 5.2 through 5.4 had no impact on linoleic acid content. However, this conclusion could be related to Switzerland environment, where minimal temperatures may have been much different than those in the current study, or the study being carried out with low linolenic acid varieties.

The difference of the positive impact of available moisture in the linoleic acid model (as suggested by a positive realtionship between linoleic acid and WSI) and the

negative impact of available moisture in the oleic acid model (as suggested by a negative impact of precipitation) exemplifies a negative relationship with oleic acid. Meanwhile, a similar positive impact of low temperatures in the linoleic and linolenic acid models exemplifies the positive relationship with linolenic acid (Stefansson and Storgaard 1969). This may be related to the temperature sensitivity of desaturase enzymes (Trémolières et al. 1978) affecting the decrease in linoleic acid content at the expense of oleic acid content, under certain temperatures. For example, low temperatures could drive the oleic acid desaturase to reduce the oleic content, and produce greater amounts of linoleic acid, which would, in turn spur on the desaturase enzyme that produces linolenic acid content, thereby changing both the quantity of oleic and linolenic acid, without affecting the linoleic content.

Despite Pritchard et al. (2000) and the canola quality data suggesting temperature and precipitation had no significant effect on linoleic acid content, the model determined that linoleic acid content was positively correlated with WSI summation values accumulated from seeding until the end of phenological stages 4.2 and 5.2 (E_WSISumCum and B_WSISumCum). Thus, a low WSI (the difference between precipitation and ET) from seeding through phenological stages 4.2 and 5.2, which results from low precipitation or high ET, resulted in low linoleic acid content. The selection of similar parameters in the iodine value model (E_WSISum) suggest that the selection of this parameter is also a direct result of the relationship between linoleic acid and the iodine value. As an intermediate stage between oleic and linolenic acid, linoleic acid content has been linked to the temperature effects on the oleic and linoleic desaturases (Trémolières et al. 1978).

The WSI is affected by precipitation and ET values, which, in turn, are driven by temperature. Therefore high WSI (associated with low linoleic acid content) can

result from high precipitation, low ET and indirectly low temperatures. Since these cool, moist conditions favour the production of oil (Canvin 1965; Daun 2006), it follows that they also increase linoleic acid content.

3.5.2.8 Linolenic Acid Content. The linolenic acid model selected three weather parameters (A_EToSum, EF_CDD<11Cum, and CF_CD<5), which were all positively correlated to linolenic acid content. Together these parameters explained 22.0% of the variation in linolenic acid levels, which is slightly less than any other individual fatty acids measured in this study.

While this model displayed certain environmental parameters have a significant impact on linolenic acid, it is likely that genotype could explain some amount of the remaining variation. The significant impact of variety and type on the quality parameter determined in initial statistics also support the concept of a genotypic effect. The significant impact of both environment and genotype on this fatty acid was found by Pritchard et al. (2000), who highlighted the success of breeding programs capable of altering linolenic acid content in favour of improved shelf-life and diversity of end uses (improved frying stability).

The selected parameters describe a positive impact of heat in the vegetative stage and a positive impact of cool conditions in the mid to late reproductive stages. At the vegetative stage (equivalent to phenological stages 3.2), a selection for warm (A_EToSum) temperatures was emphasized, possibly due to the requirement of adequate heat units for maximum growth, and for adequate sunlight, which allows for increased photosynthesis in both the pods and stems and for the accumulation of heat units (Thomas 1995) for the progression of growth and development (at a time when average daily temperatures are more likely to be too low than near any measure of heat stress). The encouragement of regular growth and development also ensures the

confluence of typical growing season weather with ideal developmental stages (so that maximum temperatures do not occur at early seed developmental stages). The selection of the summation version of the parameter, rather than the average version (A_EToSum versus A_EToAve) indicates that the duration of the favourable conditions is more important for growth and development than more erratic extremes.

Furthermore, the opposite effect of the parameter (-A_EToSum) was selected for the total saturated fatty acids model, emphasizing that the conditions to produce unsaturated linolenic acid oppose those to produce saturated fatty acids. Saturated fatty acid content has generally been linked to warmer temperatures during reproductive stages (Trémolières et al. 1978; Deng and Scarth 1998), which can only occur if development has not proceeded too quickly during the vegetative stage (as a result of low temperatures throughout phenological stage 3.2). An inverse relationship has been reported between linolenic and saturated fatty acid content in terms of percentage of total fatty acid content (Stefansson and Storgaard 1969; McCartney et al. 2004).

Linolenic acid has three double bonds, making it the most unsaturated of the individual fatty acids being considered in this study, and the most unlike saturated fatty acids which contain no double bonds. Despite being at opposite ends of the fatty acid saturation/unsaturation spectrum, their coexistence within the desaturase sequence suggests they still share some relationship.

The parameter CF_CD<5 refers to mid to late reproductive stage during which warm temperatures may still be needed for growth, but minimizing heat stress is imperative. The selection of cold stress days, rather than cold stress degree days highlights the importance of duration of the conditions rather than the intensity of the cold temperatures (which could actually have a negative impact, if too low). Cooler

temperatures favour the production of a less saturated fatty acid profile (Canvin 1965), while high temperatures have been shown to reduce linolenic acid content (Daun 2007).

Several laboratory studies (Trémolières et al. 1978; Yaniv et al. 1995; Deng and Scarth 1998) also found that canola receiving higher temperatures from various stages after flowering until maturity produced lower linolenic content than plants under cooler temperatures. Trémolières et al. (1978) observed a shift in desaturation activities according to temperature, with lower temperatures increasing oleate and linoleate desaturation activity, and resulting in increased unsaturated fatty acids production (including linolenic acid). They went on to suggest that this was due to changes in oxygen concentration and temperature-dependent enzymes, while Yaniv et al. (1995) attributed their results to either the activity of or the amount of desaturase enzymes. Deng and Scarth (1998) credited higher temperatures with hastened maturity leading to reduced saturated fatty acid content, which is supported by Daun (2006) who found that long, cool seasons resulted in higher linolenic acid content.

The positive impact of cool temperature on final linolenic acid content was supported by the inclusion of the parameter EF_CDD<11Cum, which describes a positive correlation between an accumulation of cold degree days (below an 11^{o}C threshold) throughout phenological stages 5.2 and 5.4 and linolenic acid content. This positive relationship between linolenic acid and low temperatures is supported by numerous studies which used 10^{o}C or 12^{o}C as their lowest temperature regime (Canvin 1965; Trémolières et al.1978; Trémolières et al. 1982; Yaniv et al. 1995). The model selection of 11^{o}C as a base temperature is just outside of the recommended temperature for canola growth (Thomas 1995) and just below the 13^{o}C threshold identified as the minimum threshold temperature at which fatty acid desaturases are

active, and used to determine the final linolenic acid content in canola (Baux et al. 2008).

Although the bulk of linolenic acid production occurs between 14 to 35 DAF (at a fairly constant rate of increase), which generally corresponds to phenological stages 4.3 through 4.4, there is additional increase or decrease in total content from 35 to 50 DAF (Deng and Scarth 1998), which is equivalent to phenological stages 5.2 through 5.4. As a percentage of total fatty acids over time, linolenic acid appears at its maximum at seven DAF/DAP and continues to decrease until approximately 21 DAF/DAP, after which it remains fairly constant until maturity (Sims 1964; Fowler and Downey 1970; Perry and Harwood 1993; Deng and Scarth 1998). Varieties that are specifically low-linolenic acid exhibit a different pattern with absolute values peaking at 30 to 40 DAF and declining to maturity, while its percentage of total fatty acids declined from 20 DAF until maturity (at 50 DAF) (Deng and Scarth 1998).

In a more recent study, Baux et al. (2008) determined that alpha-linolenic acid synthesis mostly occurred between 550 and 850 degree days, which roughly corresponds to phenological stage 5.2 and 5.4. They found that the sum of minimum, average and maximum temperatures from 41 to 60 DAF had the highest significant correlation to linolenic acid content out of any of the timeframes tested (at 0.85, 0.83 and 0.65, respectively).

3.5.2.9 Saturated Fatty Acid Content. The model for saturated fatty acid content selected five weather parameters, -A_SDD>19, -A_EToSum, B_AveT, -B_MaxT and BF_CD<17, which collectively explained 49.1% of the variance in total saturated fatty acid values. This was the greatest amount of variance explained by any of the quality parameter models in this study. All the weather parameters selected were

temperature-related factors, four throughout the course of phenological stage 3.2 or 4.2 and one parameter which was measured across stages 4.2 through 5.4.

The canola quality results compliment the model, determining a significant effect of temperature, but no significant effect of precipitation on total saturated fatty acid content. Similarly, the majority of research on (total and individual) saturated fatty acids investigates the impact of temperature, similar to the model-selected parameters in the current study. One study identified that rainfall had a significant effect on stearic acid (a saturated fatty acid) content, although this may have been a result of the study being conducted in Australia, where moisture stress is a regular concern (Pritchard et al. 2000).

Phenological stages 3.2 and 4.2 describe the vegetative through early reproductive stage where flowering begins and before seed development. This stage impacts plant growth and development during a time period when cooler temperatures favour maximum phenotypic expression of genetic potential (Bahrani and McVetty 2007). No substantial saturated fatty acid development occurs during stages 3.2 or 4.2. It begins at about 14 DAF/DAP, increases at a very moderate rate until approximately 30 to 35 DAF/DAP, then gradually declines until maturity. Fatty acid content, as a percentage of total oil, peaks between 14 and 20 DAF/DAP then declines until about 40 DAF/DAP (Sims 1964; Fowler and Downey 1970; Perry and Harwood 1993; Deng and Scarth 1998). Therefore, since fatty acid desaturation follows the progression from saturated fatty acids to oleic acid to linoleic acid to linolenic acid, it follows that the corresponding timeframe which affects each of these fatty acids would also progress in chronological order, which has been exhibited to some degree with the fatty acid models (Stumpf 1972). The relationship between saturated fatty acids and oleic acid was emphasized by the selection of parameter (C_CD<17) for the

oleic acid model, and the selection of the similar parameter (BF_CD<17) for the saturated fatty acid model (which both describe similar cool conditions, over different timeframes).

Interestingly, the all the parameters selected by the model to explain the variation in total saturated fatty acid content referenced phenological stage 3.2 and 4.2, which was somewhat surprising because these stages precede the start of fatty acid synthesis. The reason these parameters were selected could be due to the indirect effects of the conditions during the vegetative and early reproductive stages. This could also be linked to an impact on enzyme synthesis, which may require optimal growing conditions earlier in development to ensure adequate nutrient uptake for future enxyme production.

The two parameters referencing phenological stage 3.2 both identified a negative impact of heat. One parameter pointed out a negative relationship between saturated fatty acids and an increased number of stress degree days above 19^{o}C throughout phenological stage 3.2 (-A_SDD>19). It favours a lack of heat stress, with an emphasis on the intensity of stress (by selecting stress degree days over stress days). Deng & Scarth (1998) found that increased temperatures only had a significant impact on saturated fatty acids in the case of high temperatures, which is similar to Canvin (1965) who only noted an increase in palmitic acid at the highest of four temperature regimes (26.5^{o}C). Similarly, Aksouh-Harradj et al. (2006) found that an extreme heat treatment (reaching 38^{o}C) had more of an impact on saturated fatty acids than the moderate heat treatment (reaching 28^{o}C), with palmitic acid less responsive than stearic acid. Furthermore, Aksouh et al. (2001) determined that saturated fatty acids were only affected by high temperatures in the case of extreme heat treatments.

A negative relationship with the summation of reference evapotranspiration throughout phenological stage 3.2 (-A_EToSum) was also selected by the model. It could represent an opposition to high temperatures (which would produce a greater EToSum value), or may have been selected to oppose the conditions that favour increased linolenic acid values (since A_EToSum occurs in the linolenic acid model too). The importance of this timing likely has to do with regular plant growth and development, favouring maximum phenotypic expression of genetic potential (Bahrani and McVetty 2007).

Two of the model-selected weather parameters for stage 4.2 (4.2_AveT and -4.2_MaxT) describe optimal growth conditions with warm temperatures, but no extreme heat which could cause physiological stress. This is not in agreement with a winter canola study, reporting that average maximum temperatures and highest maximum temperatures had a significant positive effect on palmitic acid and stearic acid content, respectively (Pritchard et al. 2000). However, these temperatures were measured over the spring season, during maturation, rather than during vegetative through early reproductive stages. Trémolières et al. (1978) determined that both palmitic and stearic acid reaction was somewhat variable to heat treatments at various stages in seed development. The lowest content corresponded to the minimum and maximum temperature regimes (of 12°C/27°C and 4°C/33°C). The highest values occurred at moderate temperatures and favourable growing conditions.

The positive relationship between saturated fatty acids and cold (stress) days below 17^{o}C throughout phenological stages 4.2 through 5.4 was suggested by the model selection of one parameter (BF_CD<17). The cool conditions over an extended period of the growing season may reflect a positive impact of cool temperatures and optimal growing conditions over the period of seed development on saturated fatty

acid content. These conditions will extend the period of time required to reach maturity providing more time for oil and saturated fatty acid production (Yaniv et al. 1995). In both the 2008 and 2009 growing seasons in western Canada, seeding dates were relatively late, therefore it was very important to have an extended growing season to facilitate oil and saturated fatty acid synthesis for as long as possible.

3.5.2.10 Iodine Value Content. The iodine value model selected five weather parameters, including four temperature-related parameters and one precipitation-related parameter, which together explained 39.9% of the variation in sample values. While iodine values are commonly used in the canola industry (DeClercq 2008; Barthet 2009), they are not commonly reported in canola quality studies. For this reason, many of the inferences and discussions around the weather parameters selected by model will be related to individual or groups of fatty acids more commonly reported. The dominant stage impacting this quality parameter was 5.2, followed by stage 5.4, 3.2 and 4.4. These phenological stages correspond to specific sections of fatty acid production, with stage 4.4 corresponding to portions of the production of saturated and unsaturated fatty acids (Fowler and Downey 1970) and stages 5.2 and 5.4 corresponding to the final changes in fatty acid levels before desiccation (Perry and Harwood 1993). This may also be the reason phenological stages 5.2 and 5.4 were also referenced in the oleic, linoleic and linolenic models, and the reason phenological stage 4.2 was referenced in several of the parameters of the saturated fatty acids nmodel.

The temperature-related weather parameters in the model describe a positive impact of warm temperatures throughout stage 3.2 (A_EToSum), a positive impact of high temperatures throughout stage 4.4 (D_SDD>31), a negative impact of extreme temperatures from seeding through stage 5.2 (-E_RangeTCum) and positive impact of

cool temperatures throughout stage 5.2 (F_CDD<5). These trends are best explained by a combination of the weather conditions suitable for ideal canola growth (Thomas 1995) and those which promote unsaturated fatty acid production.

Since iodine value is a measure of the degree of unsaturation, it would be expected that the iodine value model may include weather parameters which oppose those in the saturated fatty acid model. The positive impact of A_EToSum on the iodine value model and negative impact of the same parameter on the total saturated fatty acid model describes the opposition between these quality parameters. This is supported by the results, which determined that cool temperatures were associated with higher iodine values and warm temperatures were associated with lower iodine values.

A long term increase in iodine values has been reported for canola oil, with the increase during the seventies attributed to breeding for increased linolenic acid content (Daun 1981). This positive relationship between linolenic acid and iodine values is exemplified by the positive impact of A_EToSum appearing in both models. Data from the CGC Harvest Survey (Barthet 2009) also showed a strong relationship between linolenic acid content and iodine value, making the similarities in parameters chosen for their respective models understandable.

As a large percentage of the total fatty acid content and as the least unsaturated of the fatty acids, oleic acid has been noted for its strong negative relationship with iodine values (Siemens and Daun 2005). The iodine value is a measure of the degree of unsaturation and oleic acid is only one double bond away from being saturated, so an increase in oleic acid content would result in a decrease in iodine value. The iodine value model supported these findings by selecting weather parameters F_CDD<5, and D_SDD>31 while the oleic acid model included the same parameters with opposing

signs (-F_CDD<5 and -D_SDD>31). The selection of D_SDD>31 for the iodine value model and –D_SDD>31 for the oleic acid model further highlights the impact of high temperatures and heat stress on the fatty acid profile of the canola oil during stage 4.4 at the end of flowering, when the pods are filling and the fatty acid profile is still changing. Oil biosynthesis is vulnerable at this stage (which normally occurs in late July to early August), when the highest maximum temperatures are most frequently recorded in western Canada (Environment Canada 2013).

The selection of the parameter -E_RangeTCum describes the negative impact of extreme temperatures on the iodine value, and likely a positive impact of moderate temperatures. DeClercq (2008) suggested that hot and dry conditions result in lower iodine values while cool and wet conditions resulted in higher iodine values (likely due to the emphasis on less saturated and more unsaturated content). The high iodine values under cool temperatures and lack of extreme heat is likely related to the membrane physiology of the canola plant and its need for unsaturated fatty acids in the presence of cooler conditions (Canvin 1965).

The selection of E_WSI_Sum in the iodine value model is similar to the selection of E_WSI_SumCum in the linoleic acid model (another fatty acid with a high level of unsaturation), indicating a positive effect of high precipitation or low ET on iodine value. However, the effect of precipitation on iodine value was not always consistent in DeClercq (2008). Meanwhile, Haagenson and Wiesenborn (2011) reported that rainfall did have a significant effect on iodine values in an experiment with one variety at two locations over four years. However, another experiment they conducted, using several varieties over six years, determined that the effect of rainfall was not significant. The discrepancy in conclusions may be as a result of different

background conditions, such as a dry winter before one season, or higher than average temperatures which created a moisture deficit earlier in the growing season than usual.

3.6 Conclusion

The statistical relationshipns between growing season weather and canola quality illustrate that weather parameters make up only a portion of the total environmental impact on canola quality parameters. Other important factors including soil characteristics, available plant nutrients and farm management practices are also important. However, the nature of this study and the sample set it includes does not fit any typical experimental design that facilitates LSM statistics. The results generated should be considered as indicators rather than definite conclusions. The exclusion of lower grade canola samples likely limited the range of quality values attained. Consequently, the relationships between quality and weather parameters that were derived will not reflect the full range of canola quality that can be expected and will limit the reliability of some of the predictive models.

The predictive models for oil content and for individual fatty acids (oleic, linoleic, and linolenic acid) explained a substantial (22.0 to 25.5%) percentage of the variance (of their respective quality parameters). This suggests that the models were successful at isolating the impacts of weather parameters on quality despite the successful breeding efforts maintaining high levels of oil and oleic acid content, and low levels of linolenic acid across a wide variety of weather conditions.

Although the chlorophyll model accounted for a lower percentage of variation (6.6%) and was significantly different between varieties, it had an extremely high range in values (resulting in a high standard deviation). Therefore, despite the differences amongst varieties suggesting some breeding success, chlorophyll is still

largely impacted by additional factors (such as growing season duration, due to the timeframe required for chlorophyll degradation) as shown by the large variance across samples. It was hypothesized that some of the environmental impacts on chlorophyll content were not fully captured due to the failure to measure the impact of temperature at swathing/harvesting or shortly after (since the crop did not complete the phenological stage over which it would have been measured).

Related to both of these scenarios but uniquely different, the weather parameters in the glucosinolates model accounted for a fairly high percent of variance (43.5%), but the total glucosinolates values had only a moderate to low standard deviation and showed no significant difference between varieties (unlike chlorophyll), which could have impacted the degree of predictibility in the final model.

The stability in expression of total glucosinolates may also be due to successful breeding programs which have not only limited the genotype by environment interaction, but have been successful across all genotypes investigated in this study (resulting in a lack of difference in glucosinolates values between varieties). Therefore, the low variance, which may have been instrumental in the success of the model (measured by a high percentage of variation accounted for) is also indicative of the minimal difference between varieties and may all be tied back to the success of agricultural companies and their breeding programs.

Also related to oil content but not as undesirable as glucosinolates, protein content has a slightly lower percent of variation accounted for by the model parameters (38.7%), but moderately low variance and no significant effect between varieties (genotypes). The explanation for this quality parameter may not stem from minimal breeding efforts to protein directly, but from indirect impacts from extensive

breeding efforts towards oil content (to which it is indirectly linked), giving it a low variance but preventing significant varietal differences.

Finally, the total saturated fatty acids and iodine value, which both represent the combination of several individual fatty acids (similar to glucosinolates) are able to explain a large portion of variation with the parameters in each of their models at 49.1% and 39.9%, respectively, and have significant effects of genotype and moderate to low variance. These results are likely due to the nature of the parameters representing many fatty acids and some of the breeding success of individual fatty acids showing through.

The weather parameters that were selected for the predictive models identified both the specific impacts on the quality parameters and the trends that the combinations of the specific weather parameters represent. The number of weather parameters selected and the relationships (positive or negative) that they had with each quality parameter offer further insight into the nature of the quality parameters. In general, the models with positive relationships to weather parameters were either quality parameters bred for increased values (such as oil and oleic acid) or quality parameters which favoured better phenotypic expression or plant health (glucosinolates and oleic acid).

Alternatively, negative relationships were generally associated with quality parameters which increased under stressful growing conditions (protein and glucosinolates) or were largely influenced by other quality parameters (ex. linolenic acid and iodine values).

In general, the models emphasize the importance of the plant's physiology, including the steps and components involved in seed development, including the synthesis of several pathways (ex. oil production, fatty acid synthesis and the

desaturation progression). The impact of weather parameters on plant health and the ability to phenotypically express the full potential of the genotype also weave throughout the models, along with the impact of specific conditions to influence nutrient uptake (ex. S uptake in glucosinolates) and impact of the length of the growing season for required time to complete biosynthesis (of fatty acids) or degradation (of chlorophyll).

These processes are especially important according to the stage in the growing season (and resulting weather conditions) that they occur during and the intensity of duration of the conditions. This interaction of physiology and environment brings out the impacts of heat and cold stress (according to the vulnerability of the plant), the length of the growing season or available development time (for the crop), as well as overall health of the plant (ability for maximum phenotypic expression of genotypes).

More specifically, the trends that emerged were unique to each quality parameter. Oil content was associated with the positive impact of minimum temperatures (especially throughout phenological stages 4.3 to 5.2). Protein showed an inverse relationship to oil content, with maximum values cultivated from cool phenological stage 4.2, high temperatures and low precipitation throughout phenological stage 4.3 through 5.2, and extreme values in phenological stage 5.4.

The weather conditions and time periods selected by each model generally conformed to well-documented knowledge of canola physiology. For example, the well-known negative relationship between oil and protein (Canvin 1965; Pritchard et al. 2000; Aksouh et al. 2001; Si et al. 2003; Chen et al. 2005; Daun 2006; Gunasekera et al. 2006b) was highlighted by the selection of similar variables (ex. E_CD<14) and with inverse impacts in each model.

Two trends emerged from the chlorophyll model, which had a negative intercept (possibly as a result of a low expression for canola grown under optimal conditions). There is a positive impact of cool temperatures throughout the reproductive stage (primarily phenological stage 4.2 followed by 4.4 and 5.2), and a positive impact of adequate moisture at the end of flowering (primarily) and throughout the reproductive stage. Together, the parameters selected for the glucosinolates model emphasized three trends, including the negative impact of heat early in the reproductive stage, the positive effect of heat (including the duration and intensity of warm temperatures throughout the growth stages) and the negative effect of cool temperatures on final glucosinolates content.

The oleic acid model brought to light three trends, including how (similar to the oil model) low temperatures during phenological stages 4.3 and 4.4 have a positive impact, hot and dry conditions throughout stages 5.2, 5.4 and 4.3 have a positive impact, and a conditions favouring a longer maturation period (and increased oil production) allow for maximum expression of this quality parameter.

The main themes emerging from the linoleic acid model was the positive impact of low temperatures throughout pod and seed development and the negative impact of moisture stress throughout canola growth until late maturity. As a kind of intermediary step between oleic and linolenic acid, it was influenced by both conditions which promoted or diminished the content of other fatty acids (included saturated and varying degrees of unsaturated fatty acids).

The linolenic acid model emphasized two trends which include the positive impact of moderately warm vegetative stage (both in opposition to saturated fatty acids and in support of favourable growing conditions), and a positive effect of cool temperatures throughout pod and seed development (at the final stages of fatty acid

synthesis). This promoted the production of less saturated (and more unsaturated) fatty acids.

With a strong focus on phenological stage 3.2 and 4.2, the three trends that emerged from the total saturated fatty acid model, were cool temperatures throughout stage 3.2 and moderately warm temperatures throughout stage 4.2 (related to preferred growing conditions), as well as cool conditions throughout flowering and pod production and development.

Finally, trends generated by the selection of weather parameters in the iodine value model were the positive impact of warm temperatures during the vegetative stage and phenological stage 4.4, negative impacts of long periods of extreme temperatures and moisture stress, and positive impact of cool temperatures late in development (stage 5.4).

There were several trends within the fatty acid profile. The impact of successive phenological stages on progressively less saturated fatty acids was detemined. More specifically, the saturated fatty acid model emphasized the impact of weather parameters measured throughout phenological stage 4.2, while oleic acid, linoleic acid, linolenic acid and iodine value where primarily influenced by weather parameters measured over stages 4.3 or 4.4, 4.3 to 5.2, 4.3 to 5.4, and 4.4 through 5.4, respectively.

Opposite relationships were found between weather parameters and saturated versus unsaturated fatty acids. Several weather parameters in the oleic acid model oppose those from the iodine value model, including –F_CDD<5 versus F_CDD<5 and –D_SDD>31 versus D_SDD>31, respectively. Likewise, a weather parameter in the linolenic acid model opposed one in the total saturated fatty acid model

A_EtoSum versus - A_EtoSum, respectively. These trends were in agreement with the desaturation activities in Trémolières et al. (1978).

The models accounted for considerable amounts of variance within each of the nine quality parameters. However, there were several challenges with this data including lower presumed accuracy of precipitation values, unequal number of samples by genotypes and only one sample per location which limited ability to analyze genotype effects and Genotype by environment interaction. Furthermore, an even larger dataset including more growing seasons may provide an greater range in weather conditions (in terms of both temperature and precipitation) creating more scenarios for canola crops to respond to (as shown by quality parameters. This, in addition to including more canola samples which remained in the field until the end of phenological stage 5.4 was completed would strengthen the models.

It should also be noted that it is possible for interactions of multiple weather parameters to impact canola quality as well. That is to say that, although it is possible for several weather parameters to individually have little impact on a quality parameter, together they may complement each other to produce a greater impact than the sum of each parameter individually. This may have been the case in Bahrani and McVetty (2007) where field-grown canola seeds subject to varying conditions produced significantly higher oil content than greenhouse-grown seeds grown under controlled conditions. (Although the field-grown crop also had cooler than normal mean temperatures throughout the growing season and slightly wetter than usual conditions, which is favourable for oil production.)

Despite all this, these nine predictive models could be relevant to canola breeders interested in which weather parameters plants should be bred to be less impacted by or more adaptable to. The models could also be used by grain buying

companies to be able to advise potential customers on what the expected final crop should bring, in terms of canola quality (oil, protein, chlorophyll, glucosinolates, oleic acid, linoleic acid, linolenic acid, and total saturated fatty acid content, as well as iodine value).

Finally the results from the models could be used by agronomists and agricultural professionals to better understand the physiology of the crop and phenological stages that are most vulnerable to specific weather conditions, as well as a hypothesis behind the reason for this reaction.

As is the case with models, these predictions should not be expected to be entirely accurate each year, but over many years, they should be fairly close to the average conditions.

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OVERALL SYNTHESIS

This investigation examined the phenology of current varieties of canola and quantified the effects of various weather parameters measured over the duration of specific canola growth stages on nine quality parameters, most of which have been identified as ongoing issues in the canola industry (Hickling 2005).

The phenology study investigated the development of current canola varieties and attempted to compare them to varieties grown one decade earlier, in terms of heat unit accumulation by growth stage. This investigation included a field study for the production of an updated P-Day index, a weather data collection verification test and additional canola samples for the predictive model study. The newly created P-Day index was used to model the phenological development of canola crops in western Canada throughout the growing season without direct observation. The predictive models quantified the effects of weather parameters on the oil, protein, total glucosinolates and chlorophyll content of canola, as well as the oleic acid, linoleic acid, linolenic acid, total saturated fatty acid content, and iodine value of canola oil.

Kc coefficients were created in order to calculate canola crop evapotranspiration (ETc), an estimate of the water demand by the crop throughout its growth period.

The field study provided seven additional sample sites for the predictive model dataset, and observations from the field study which provided a better understanding of canola development and how varieties react to their environment.

A few themes regarding canola and meteorological impacts on the crop emerged from the two studies. Possibly due to some concerns with precipitation data and the general adequate moisture level across western Canada (Agriculture and Agri-Food Canada 2013), canola quality parameters were primarily impacted by air

temperature rather than precipitation. However, the time at which specific temperatures were reached affected whether temperatures would have a positive, negative or neutral impact on oil content or other quality parameters, especially depending on the temperature intensity and duration over which it lasted (relative to the canola growth stages). The western Canadian prairies have a relatively short growing season, and therefore temperature is very important for heat accumulation within the limited frost-free days. Despite the short growing season, canola was found to be resilient and adaptable, especially in terms of late seeding dates, under which it was still able to mature and produce high quality oil before the end of the growing season. Breeding successes are also to be credited for the robustness of canola quality parameters, the production of specific fatty acid profiles in oil, and the herbicide tolerant traits in Liberty Link™ and Roundup Ready™ varieties across a range of environments.

Canola quality parameters are affected by genotype, environment and genotype by environmental interactions. There were strong relationships between related quality parameters (across the fatty acid profile), inverse relationships between other parameters (oil and protein) and some quality parameters which represented a combination of individual components and their specific relationships with quality parameters (iodine value and total saturated fatty acids).

The predictive models focussed on predicting mean, rather than extreme, values. Furthermore, the models only provided statistical relationships and did not provide any understanding of the physical or physiological link between weather and canola response. The models were also created using only Canada No.1 canola samples, which may have added some bias by limiting the variation in quality data,

potentially impacting the resulting relationships which were determined, as well as suggesting an overestimation of robustness in quality parameters.

The nine models explained between 7% and 49% of the variation within canola quality parameters. The results indicated that environment, especially temperature, had a significant impact on canola quality. Some of the weather impacts were very similar to those reported in previous literature, while some were slightly different or more detailed.

The oil content model reaffirmed that low temperatures throughout development produced greater oil content but suggested that temperatures of 11^{o}C to 14^{o}C or lower throughout phenological stages 4.3 to 5.4 produced greater oil content. The protein content model suggested that cool temperatures during phenological stage 4.2, as well as high temperatures accompanied by low precipitation throughout phenological stages 4.3 through 5.2 (creating a high stress situation), and extreme temperatures (high and low, which possibly shorten the growing season reducing time for oil production) throughout phenological stage 5.4 favor greater protein values. Even though weather parameters measured throughout phenological stage 5.4 would not be expected to affect final canola quality, each of the nine models selected at least one parameter partially or entirely from this phenological stage.

The total saturated fatty acid content model showed a positive relationship with cool and moderately cool temperatures throughout phenological stages 3.2 and 4.2 (vegetative and early reproductive stages). Total saturated fatty acids were also a part of a group of quality parameters, with glucosinolates and iodine value that described a combination of individual constituents. As expected, their respective models were able to explain a greater amount of variation than models for individual fatty acids.

The lower percentage of variations explained by the individual fatty acid content models may have been partly due to breeding successes of specific fatty acid profiles, across any environment. Additionally, this could have resulted because of the complex interactions between oil content and the individual fatty acids measured. Oleic acid content was mainly explained by a combination of the parameters which promote greater oil content (positive effect of cool temperatures measured across phenological stage 4.3 through 4.4) and those which favour more saturated and less unsaturated content (hot and dry conditions throughout phenological stages 5.2 through 5.4). Conversely, linolenic acid appeared to be strongly impacted by conditions which favour unsaturated content and reduce the production of saturated fatty acids (cool temperatures throughout phenological stages 4.2, 5.2, and 5.4). The intermediary linoleic acid content increased with ideal growing conditions (cool without moisture stress) which shared similarities to the iodine model and the linolenic acid models.

Quantifying the effect of environment on the quality parameters also highlighted other areas which were potentially the result of breeding success, such as the low total glucosinolates content across all samples from their range of environments. Alternatively, the variability in chlorophyll content and relatively low percentage of variation accounted for by the weather parameters suggests that there is still room for improvement of the genotypic expression or stability in genetic expression across environments (genotype by environment interactions) of chlorophyll in canola.

Despite these conclusions, there is still a need for more research in the modelling of canola quality. The non-traditional experimental design used in this study limited the quantification of genotype by environment interaction, so including

replicates of several varieties at sites, and using equal number of samples from each variety would improve on this. Although there is an impressive number of weather stations collecting data across western Canada, increasing this number and improving on the accuracy of precipitation data would offer more accurate accounts of the weather conditions. Possibly adding more crop-related measures (such as the number of consecutive days above a certain temperature) to the analysis could also make use of additional site specific weather data. Similarly, incorporating soil information into the model projections may produce more successful outputs.

Another consideration for a future study could include investigating effects of growing season weather conditions in relation to normalized data (in reference to climatic normals for the region). This is suggested despite few significant differences in the separation of low and high precipitation and warm and cool temperature values, and with the understanding that varieties are often grown in clmatic regions that are best suited for them. Another possibility for a future study would be quantifying the effects of weather on each growth stage, where after each growth stage throughout the growing season, plants were transplanted into a greenhouse to finish up development under ideal conditions and then harvested and analyzed for various quality parameters.

The weather cannot be changed in order to adjust canola quality, but the applications from this study can still benefit producers, plant breeders, and marketing opportunities. Producers can make management choices (ex. seeding date, rate, applications, harvest method, etc.) in order to align the growth stages with the type of weather that typically occurs during a certain time frame. Similarly, plant breeding could work on altering the length of growth stages to align stages with preferred climatic normals. Breeders could also alter the expression of certain quality parameters (ex. oil production) so that the plants are less impacted by weather

parameters that affect them negatively (ex. high temperatures) or alter the expression of certain quality parameters so quality parameters express greater benefit from weather parameters that affect them positively (ex. low temperatures). However, it must be acknowledged that the quality parameters interact with each other, therefore improvements to one may cause another to deteriorate. Quality parameters must be prioritized (ex. how the amount of protein produced can be disregarded in in place of high oil production).

Finally, reliable predictions of crop quality can be an asset to those marketing Canadian canola. Canada exports over 85% of the canola grown to 55 different markets (Canola Council of Canada 2010), so it is imperative that reassurance of the quality of crop being produced is provided, to prevent potential customers from buying from a competitor. With quality driven countries like Japan among Canada's top customers, it is even more important for maximum effort to be put into maintaining our quality and letting customers have an estimate beforehand. As a heart-healthy product, canola oil is known for its ideal fatty acid profile, which has also diversified to fit specialty markets that require specific quantities of oleic, linoleic and linolenic acid content. Maintaining these markets and assuring customers that the current crop year has produced preferred target profiles is crucial and could be achieved with the use of predictive models.

Furthermore, concerns of climate change and evidence of more extreme weather than ever before will drive the need for an understanding of the effects of weather on canola to escalate over time, fostering more research in this area.

As the canola industry in Canada continues to evolve, prediction studies will continue to be relevant and as an increased number of weather stations and canola quality data are collected, this will facilitate improved predictive models. As

producers continue to eliminate inefficiencies and focus more and more on the details of production practices, the ability to estimate and minimize environmental impact will become even more important, especially if canola production increases and moves into increasingly marginal land.

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5.0 APPENDICES

Appendix A1. Crop Coefficient Determination

The Kc value is used to describe the evapotranspiration of a specific plant at a certain point in development, in relation to a standard vegetated surface. Although the pattern of growth and development has some similarities across field crops, each species is unique in the sequence in which it accumulates dry matter and transpires (Allen et al. 1998). Canola is unique in that it develops from a low-lying, leafy vegetative stage into an upright flowering plant which utilizes photosynthates for stem and pod production and finally seed production, in the reproductive stage (Thomas 1995). The resulting accumulation of fresh weight throughout the reproductive stage follows a unique pattern of nearly exponential increase until the peak, followed by a moderate partial decline until maturity (Perry and Harwood 1993) due to a drop in the abilty of the plant to transmit water as it ripens (Thomas 1995). Therefore, this dynamic growth pattern requires Kc values that correspond to each growth stage.

The crop coefficients that the FAO has created provide a strong, internationally-recognized basis on which to build a daily Kc index. The FAO index breaks the canola growth stages into three stages: initial, mid and end growth stages with values 0.35, 1-1.15 and 0.35, respectively. It is stated that these values are most appropriate for "non-stressed, well-managed crops in sub-humid climates ($RH_{min} \approx$ 45%, $u_2 \approx 2$ m/s" (Allen et al. 1998). Since the current study was carried out under approximately these conditions, these values are applicable and were directly used for growth stages 2.2, 4.2, 4.3 and 4.4 and used for verification of growth stages 3.2, 5.2 and 5.4. Another study carried out in South Australia with winter canola utilized these values and yielded accurate results, in support of these values (ICMS 2004).

Along the lines of the three Kc values, but incorporating the period of change between them, the government of British Columbia's Ministry of Agriculture, Food and Fisheries described the crop coefficients according to four distinct growth stages: initial, crop development, mid season and late season, with the duration of these stages subject to change depending on the climate, latitude, elevation and seeding date. This source also recognized that the evaporation portion of evapotranspiration increases with greater surface of exposed soil, while transpiration portion (of evapotranspiration) increases with amount of foliage produced and resulting canopy cover (which decreases again when the plant begins to dry down). They also described the point of maximum evapotranspiration as the mid-season growth stage, when the canopy cover is between 70-80%, and solar radiation and air temperatures are at an annual maximum. This may be partially due to the high temperatures driving higher transpiration rates in order to cool the plant and prevent heat stress (Kutcher et al. 2010). In order to carry out maximum ET mid season (Van der Gulik and Nyvall 2001), and if irrigation can be provided at one point in the growing season, it should be provided at flowering (Istanbulluoglu et al. 2010). Transpiration has also been shown to be affected by photosynthetically active radiation (producing a positive curvilinear response), and shares a positive correlation with air temperature (Singh et al. 1982). Similarly, AARD (2009) reported that canola does not require as much moisture for transpiration under cool conditions as it does under warm, dry conditions, since less available soil moisture is needed for transpiration cooling (AARD 2009). This information was combined to determine Kc coefficients for stages 3.2 and 4.2 through 5.4.

A more thorough set of crop coefficients corresponding to canola growth was reported by Agrimet (1994), where growth was described as percentage of growth

stages from 0 (%) through 200 (%). According to this scale 100% emergence was equivalent to 0% growth stage and a Kc value of 0.20, 50% heading was equivalent to 100% growth stage and a Kc value of 1.00, and dead leaves and stems were equivalent to 200% growth stage and a Kc value of 0.28. Since this study was carried out in Montana, the latitude and longitude were relatively close to the western Canadian prairies (as compared to a study in Australia or Europe, which the FAO values would likely consider along with values from North America), these values were also considered in the production of coefficients for stages 3.2, 4.2, 4.3, 5.2 and 5.4 (Agrimet 1994).

Aside from the input into the Kc value calculations, the values had to correctly link to the appropriate growth stages (which then would be represented by corresponding P-Day totals). While this selection incorporated the information on basic growth stages from Allen et al. (1998) and Van der Gulik and Nyvall (2001), and the few stages referenced in the Agrimet study, it also largely used the work from Thomas (1995) and AARD (2009). Despite both of these sources plotting daily ET values rather than Kc values against calendar units (rather than growth stages or P-Day totals), these studies were carried out across western Canada. Furthermore, the calendar days could be roughly equated to growth stages based on average climatic data and average growth throughout the western Canadian growing season (and observations made in an intensive field study described in chapter two).

The curves presented by Thomas (1995) and AARD (2009) described much of the variation in ET throughout the growing season of spring canola explaining that canola will continue to use 7 to 8 mm/day throughout the flowering stage, under optimum conditions (AARD 2009). While these studies reported peak daily ET rates between 7.5 to 8 mm/day (Thomas 1995; AARD 2009), winter canola has reported

daily peak values of only 6.5 mm/day (Istanbulluoglu et al. 2010). Thomas (1995) and AARD (2009) studies which marked early July as the point in which maximum ET occurred, were supported by a study in Saskatchewan, which mentioned that the low yields were reported in years which had a precipitation deficit in the first week of July (Kutcher et al. 2010).

Since the ET values given in this study were actually ETc values (not Eto values), they had already incorporated the Kc coefficient. Without knowing the ET of a reference crop (Eto) in the same location throughout the same growing season, Kc values cannot be calculated. Therefore, they were used to compare against final ETc values in the current study, and validate the Kc values that the new index proposed.

Both Thomas (1995) and AARD (2009) data referenced a growing season that began at the beginning of May. However, since the majority of sample sites were seeded between mid to late May, Thomas (1995) and AARD (2009) curves were shifted to the right to fit the growing season of the samples in the current study. (Of course this was just an estimation, as it is understood that the crop would make adjustments accordingly, depending on the seeding date and growing season weather). The 6 growth stages used in the new P-Day index were then inserted along the ET curves, according to the average calendar dates that each growth stage corresponded to (according to the data collected). However, since ET is also a function of solar radiation, which changes with the day of year (and would be lower in September than August, when development concludes on the graph) the final ETc values were not quite as high as the graph values. (The lower values could as be as a result of more efficient canola varieties used in the more current study.)

Table A1.1 Summary of development of crop coefficients.

Growth Stage	P-Day Total (X)	K_c	Explanation
Seeding	0.00	0.20	Taken from Agrimet (1994) chart
50% emergence	54.50	0.20	Taken from Agrimet (1994) chart
2.2	139.7	0.35	Taken from initial stage in Allen et al. (1998)
3.2	297.86	0.85	The estimate used in the Agrimet (1994) document 42.5% growth stage and in agreement with the transition between initial and mid stage from Allen et al. (1998). This is validated with ETc values produced in Thomas (1995) and AARD (2009)
4.2	405.38	1.075	Assuming that the stage 4.1 was 1.0 from Allen et al. (1998) and 4.3 would be 1.15 (the top of the range), this was a mid-point between them. Confirmed by similar value of 1.0 value used in Agrimet (1994). Validated with ETc values produced in Thomas (1995) and AARD (2009)
4.3	478.88	1.15	Taken from peak of mid stage in Allen et al. (1998)
4.4	601.14	1.05	Assuming that the stage 4.3 was 1.15 from Allen et al. (1998) and 5.1 would be about 1.0, mid-point between the two would be 1.075, but since the curves from Agrimet (1994) and Van der Gulik and Nyvall (2001) suggest a more dramatic drop after the peak ET, this value needed to be lower than 1.075, so two-thirds of the way between 1.15 and 1.0 (1.05) was used (as opposed to half-way)
5.2	734.89	0.80	Assuming that the stage 5.1 would be about 1.0, stage 5.5 would be 0.35, and the ET dropped at a constant rate between each stage, 5.2 would be 0.8375 according to Allen et al. (1998), but (again) since Agrimet (1994) and Van der Gulik and Nyvall (2001) suggest a dramatic drop after the peak ET, so it was decided that this value should be a little lower than the value used for stage 3.2, so 0.8 was used. This is confirmed by Agrimet (1994) and Van der Gulik and Nyvall (2001) graphs as well as the estimated values for transposed Thomas (1995) and AARD (2009) graphs
5.4	814.68	0.60	Assuming that the stage 5.1 would be about 1.0, stage 5.5 would be 0.35, and the ET dropped at a constant rate between each stage, 5.4 would be 0.5125 according to Allen et al. (1998), however, since Thomas (1995) and AARD (2009) graphs did not drop nearly as low as final Kc values of 0.35 would produce, this value had to be higher than 0.5125. If the estimate for 180% growth stage was used from the Agrimet (1994) graph (where stage 5.5 is 200% growth), the Kc would be 0.60. Since using the Kc of 0.60 would produce values that would make sense with Thomas (1995) and AARD (2009) ETc values (once adjusted according to the seeding dates in the current study), this values was used for stage 5.4

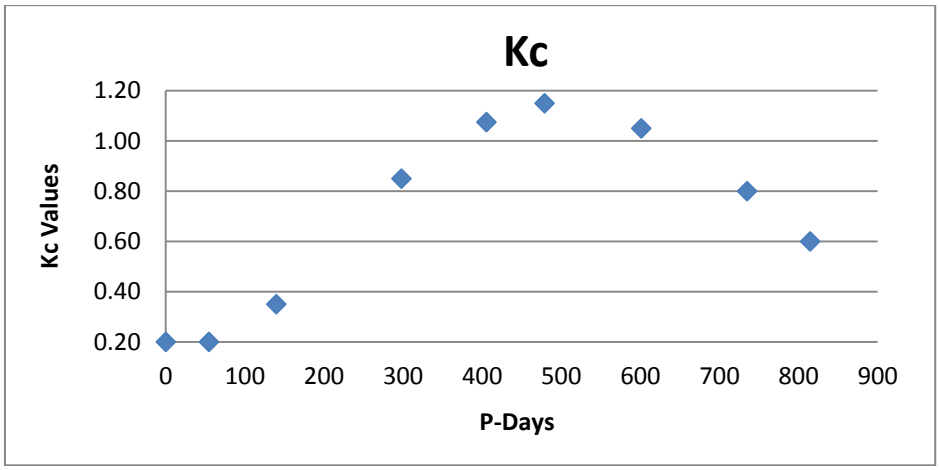

Figure A1.1 Crop coefficient values (Kc) and corresponding P-Days.

These values were plotted on a graph (above) an since they produced a curve very similar to Thomas (1995) and AARD (2009) studies, it was tested out with ETo values from randomly selected samples. This also yielded acceptable results which were in agreement with Thomas (1995), Agrimet (1994) and AARD (2009) studies, so these values were considered accurate.

The equations to calculate the values between these points were then created (assuming they should follow the same relationship between points) by determining the slope between each of the two points (see below). When this series of equations (describing the Kc coefficient) was multiplied by daily ETo values of various samples, they also produced acceptable values (such as the example below).

Table A1.2 Summary of crop coefficients and corresponding equations.

Growth Stage	P-Day Total (X)	K_c	Slope	K_c equation for x
Seeding	0.00	0.20	-	-
50% emergence	54.50	0.20	-	0.2
2.2	139.7	0.35	0.0018	.0018x+0.104
3.2	297.86	0.85	0.0032	.0032x-.0916
4.2	405.38	1.075	0.0021	.0021x+.2267
4.3	478.88	1.15	0.0010	.0010x+.6613
4.4	601.14	1.05	-0.0008	-.0008x+1.5417
5.2	734.89	0.80	-0.0019	-.0019x+2.1736
5.4	814.68	0.60	-0.0025	-.0025x+2.6421

Canola has been shown to be especially affected (in terms of yield) by water stress throughout the flowering stage, making it the single most responsive developmental stage to irrigation throughout (Istanbulluoglu et al. 2010). Interestingly, crops irrigated later in development (between flowering, yield formation and ripening stages) reported the higher ET and lower WUE values than those irrigated earlier in development (Istanbulluoglu et al. 2010).

Appendix A2. Observation Dates and Accumulated P-Days for Each Field Site

Table A2.1 Observation summary of intensive field study sites.

Location	Date	P-Days*	Growth Stage†
Portage	3-Jun-09	82	1
	12-Jun-09	131	2.2
	17-Jun-09	169	2.3
	22-Jun-09	206	2.4
	3-Jul-09	300	3.1
	15-Jul-09	398	4.2
	23-Jul-09	463	4.3
	6-Aug-09	585	4.4
	13-Aug-09	644	5.1
	21-Aug-09	714	5.2
	30-Aug-09	788	5.4
Carman	3-Jun-09	98	0
	17-Jun-09	191	2.3
	22-Jun-09	222	2.4
	3-Jul-09	315	4.1
	15-Jul-09	417	4.2
	23-Jul-09	482	4.3
	6-Aug-09	605	4.4
	13-Aug-09	657	5.1
	21-Aug-09	728	5.2
	1-Sep-09	819	5.4
Oakville	3-Jun-09	77	1
	12-Jun-09	130	2.2
	17-Jun-09	168	2.3

	22-Jun-09	205	2.4
	3-Jul-09	301	3.2
	15-Jul-09	401	4.2
	23-Jul-09	467	4.3
	6-Aug-09	593	4.4
	13-Aug-09	649	5.1
	21-Aug-09	722	5.2
	31-Aug-09	803	5.4
Rosebank	3-Jun-09	102	1
	17-Jun-09	191	2.3
	22-Jun-09	227	2.4
	3-Jul-09	320	4.1
	15-Jul-09	422	4.2
	23-Jul-09	488	4.3
	6-Aug-09	612	4.4
	13-Aug-09	669	5.1
	21-Aug-09	740	5.2
	1-Sep-09	833	5.4
Jordan Corner	3-Jun-09	96	1
	17-Jun-09	189	2.3
	22-Jun-09	223	2.4
	3-Jul-09	318	4.1
	15-Jul-09	424	4.2
	23-Jul-09	493	4.3
	6-Aug-09	619	4.4
	13-Aug-09	673	5.1

	21-Aug-09	745	5.2
	1-Sep-09	837	5.4
	18-Sep-09	974	5.5
Balmoral	4-Jun-09	37	0
	16-Jun-09	110	2.2
	22-Jun-09	156	2.3
	3-Jul-09	253	2.5
	7-Jul-09	289	3.2
	17-Jul-09	373	4.2
	30-Jul-09	488	4.3
	12-Aug-09	603	4.4
	19-Aug-09	666	5.1
	1-Sep-09	778	5.2
	7-Sep-09	825	NA
Rathwell	3-Jun-09	82	1
	17-Jun-09	169	2.3
	22-Jun-09	208	2.4
	3-Jul-09	304	3.2
	15-Jul-09	403	4.2
	23-Jul-09	470	4.3
	6-Aug-09	591	4.4
	13-Aug-09	645	5.1
	21-Aug-09	717	5.2
	1-Sep-09	808	5.4

* Accumulated from the time of seeding
†Thomas 1995

Appendix A3. Basic Statistical Measures of Canola Quality Data

Table A3.1 Basic statistical measures of canola quality data.

	Oil	Protein	Chloro	Glucos	Oleic acid	Linoleic acid	Linolenic acid	Sats	Iodine value
Mean	45.09	20.14	10.92	8.61	62.73	18.74	9.47	7.02	112.62
Median	45.23	20.20	10.60	8.40	62.72	18.56	9.33	7.05	112.51
Mode	44.51	20.00	10.90	8.30	63.12	18.06	8.85	7.22	113.72
Standard Deviation	2.00	1.96	5.37	1.54	1.60	1.17	1.02	0.35	2.11
Variance	3.99	3.82	28.81	2.38	2.56	1.37	1.04	0.12	4.45
Range	9.30	10.40	25.70	8.82	8.21	7.09	6.38	1.90	11.43

Chloro = Chlorophyll
Glucos = Glucosinolates
Sats = Total saturated fatty acids

Appendix A4. Quality Data for Canola Samples across Western Canada, by Dataset

Table A4.1 Quality of western Canadian canola for the complete 2009 Field dataset.

Sample	Variety	Oil	Protein	Chloro	Glucos	C181	C182	C183	Sats	IV
1	5020	45.27	22.586	2.529	13.422	64.27	16.71	11.07	6.05	114.51
2	5020	43.77	24.888	2.627	12.506	64.98	16.12	10.89	6.06	113.67
3	5020	47.27	19.118	0	11.328	64.74	16.96	10.30	6.21	113.25
4	5020	46.89	19.709	3.267	9.752	63.52	17.62	10.72	6.23	114.56
5	5020	48.65	16.595	3.324	9.402	64.25	17.83	9.80	6.28	113.09
6	5020	47.41	17.642	5.661	8.424	64.66	17.55	9.71	6.30	112.68
7	5020	48.72	16.4	22.457	8.467	65.28	17.31	9.07	6.62	111.07
8	5020	45.52	21.401	2.043	9.577	65.18	16.47	10.27	6.13	112.79
9	5020	46.12	18.812	7.369	8.608	63.97	18.18	9.59	6.39	112.93
10	5020	46.57	20.495	13.745	10.621	64.86	16.95	10.15	6.14	113.03
11	5020	48.31	18.023	0	10.84	65.52	16.51	9.87	6.31	112.03
12	5020	45.35	22.939	1.332	12.617	65.55	16.01	10.51	6.01	112.96
13	5020	43.77	22.697	0.564	9.143	65.16	17.16	9.31	6.37	111.55
14	5020	48.34	16.877	1.014	9.565	66.13	17.04	8.64	6.50	110.20
15	5020	44.38	21.839	1.81	8.966	64.55	17.31	9.78	6.50	112.41
16	7145	44.72	20.188	6.418	8.203	62.68	18.72	10.01	6.66	113.89
17	5020	43.35	21.225	0.328	9.254	62.95	18.99	9.69	6.47	113.72
18	5020	.	.	.	.	64.49	17.90	8.83	6.84	.
19	5020	41.73	24.092	9.713	8.762	58.20	22.58	10.06	7.12	116.91
20	5030	42.76	22.211	9.99	8.359	61.66	18.32	11.24	6.77	115.60
21	5020	44.51	21.614	10.25	9.146	62.81	18.52	10.08	6.59	113.89
22	5030	43.55	21.125	8.07	8.309	62.02	18.25	11.02	6.72	115.20

Key:
Chloro = Chlorophyll; Glucos = Glucosinolates; C181 = Oleic acid;
C182 = Linoleic acid; C183 = Linolenic acid; Sats = Total saturated fatty acids;
IV = Iodine value; Variety 1 = SP Banner

Table A4.2 Quality of western Canadian canola for the 2008 Harvest Survey dataset.

Sample	Variety	Oil	Protein	Chloro	Glucos	C181	C182	C183	SATS	IV
226302	3465	42.64	22.4	20.2	6.5	63.13	18.48	8.78	7.35	110.85
2205055	7145	43.50	21.8	7.7	4.6	62.63	19.48	8.29	7.42	110.81
2205512	5020	46.69	19	17	11	64.31	18.36	8.43	7.06	110.46
2205535	5020	46.58	19.1	10.6	7.5	63.10	18.34	9.70	6.88	112.79
2205541	5020	45.50	20	14.4	9.5	63.57	18.00	9.25	7.01	111.58
2205787	5030	44.40	20.2	7.7	5.9	63.28	17.54	9.78	7.28	111.75
2205989	5020	46.67	18	9.7	6.8	62.70	19.03	9.19	7.08	112.33
2205990	5020	45.86	19.2	10.2	7.5	62.28	19.28	9.46	6.99	113.09
2206137	1841	46.34	18.9	16.4	7.8	61.06	20.38	9.32	7.23	113.60
2206381	3465	44.05	20.9	15.3	5.8	63.02	17.63	9.79	7.25	111.95
2206480	5020	48.08	16.9	8.6	7.6	65.30	17.26	8.48	7.08	109.54
2206602	7145	42.12	25.3	9.9	8.1	59.56	20.91	10.89	6.35	117.54
2206693	7145	44.22	22.5	6.6	6.7	64.24	18.34	8.19	7.16	109.88
2206762	5020	45.34	20.3	6.6	7.4	64.60	17.45	8.56	7.36	109.61
2206819	5020	44.51	20.9	12.4	8.8	62.50	18.81	9.48	7.17	112.55
2206912	5020	43.49	21.2	18.8	9.6	61.96	18.86	10.01	7.09	113.61
2206998	5020	49.15	16	15.2	5.7	63.52	18.53	9.02	7.10	111.60
2207290	5030	42.98	22	11.9	8.4	62.21	18.35	10.07	7.28	113.10
2207553	5020	42.76	21.6	7	7.5	63.99	17.93	8.40	7.62	109.50
2207659	7145	44.77	21.2	17.8	8.9	59.92	20.71	9.91	7.18	114.92
2207804	5020	43.37	21.5	14	10.6	63.41	18.03	9.32	7.15	111.61
2208015	5020	46.382	18.8	13.9	6.9	64.55	17.98	8.10	7.35	109.23
2208199	7145	42.90	21.6	5.3	8.8	63.57	19.25	7.54	7.59	109.14
2208454	5020	45.00	20.4	12.1	6.7	63.15	18.98	8.77	7.17	111.51
2208708	1	47.74	17.6	0.3	8.4	64.21	19.11	7.84	6.94	110.12
2208746	7145	45.03	20.8	15.3	7.8	61.91	19.65	9.15	7.19	112.66
2208808	7145	46.56	20.2	7.7	6.5	60.45	19.69	10.75	6.96	115.69
2208860	1	44.92	21.7	3.8	9	63.86	18.95	8.22	6.77	110.79
2209409	5030	43.33	20	15.5	6.2	61.83	18.44	10.15	7.49	113.13
2209736	5020	46.61	18.6	9.1	7.7	64.41	17.87	8.65	7.16	110.31
2209737	5020	46.24	18.8	8.2	7.9	63.34	18.54	9.07	7.08	111.69
2210087	5020	44.62	20.5	13.7	9.3	63.68	18.60	8.78	6.93	111.37
2210123	5020	45.76	20.3	16	7.7	62.35	19.39	9.49	6.79	113.43
2210190	5020	40.42	24	15.3	7.5	62.94	18.97	8.23	7.70	110.04
2210398	5020	47.06	18.7	7.8	8.4	64.56	17.39	9.00	7.07	110.59
2210576	1841	44.40	20.6	15.5	8.5	62.71	19.20	8.87	7.22	111.79
2210745	5030	47.07	17	13.1	7.1	62.37	18.18	10.28	7.26	113.35
2210808	5020	46.17	18.5	17.3	9.1	64.43	18.22	8.24	7.25	109.82
2210835	7145	48.24	16.7	4.2	7.3	62.06	20.53	8.28	7.25	111.89
2210877	5030	43.12	21.1	15.7	7.9	60.84	18.68	10.84	7.44	114.59
2210898	7145	41.94	23.1	7.9	8.3	62.34	20.19	8.02	7.33	111.02
2211271	5020	44.95	20.5	10.9	8.6	63.68	18.62	8.76	6.93	111.35
2211306	1841	41.35	23.4	22.3	9.8	58.62	20.53	11.21	7.31	116.94
2211414	1841	45.14	22	18.1	6.4	62.19	18.44	10.24	6.90	113.76
2211592	5020	44.30	19.1	19.8	8.4	64.02	19.00	7.19	7.91	108.09
2211602	5030	43.14	21.1	12.4	7.1	60.38	19.15	10.80	7.52	114.87
2212257	5020	47.09	17.9	7.5	8.6	64.80	17.28	8.85	7.12	110.16
2212267	5030	46.02	19	7.7	6.6	62.19	18.36	10.25	7.22	113.50
2212321	3465	46.09	19.8	11.3	8.6	65.41	17.03	8.34	7.19	108.98
2212396	1	46.55	19.5	5.6	7.6	63.50	18.81	8.69	6.79	111.45
2212673	7145	46.04	19.3	15.5	7.3	62.17	19.67	8.97	7.12	112.43
2212784	5020	47.53	17.6	8.5	9.5	64.28	17.08	9.45	7.18	110.99

2212828	7145	43.62	21.7	11.5	9	61.48	20.73	8.40	7.24	112.24
2213198	5020	43.78	22.1	15.9	9.3	63.63	18.16	9.19	6.89	111.73
2213310	5030	45.33	19.4	5	8.2	63.78	17.22	9.69	7.35	111.41
2213548	5030	45.40	19.2	7.8	8.2	62.37	17.91	10.37	7.31	113.22
2213637	5020	46.94	19.6	9.3	7.8	64.98	16.94	9.19	6.89	110.67
2213756	5030	43.96	20.7	6.7	6.9	63.30	17.59	9.65	7.42	111.59
2213966	5030	49.36	16.6	4.5	6.8	65.87	17.22	8.16	6.92	109.09
2214013	7145	46.67	18.9	7.6	8.5	62.73	19.90	8.42	7.00	111.78
2214045	5030	40.29	22.7	13.3	9.9	61.77	19.57	8.92	7.71	111.78
2214066	5020	46.40	19.7	8	7.7	63.79	18.21	9.11	6.89	111.63
2214276	1	45.68	19.7	6.2	8	62.18	20.15	8.55	6.92	112.27
2214320	7145	42.83	23	1.6	10.5	63.99	18.94	7.68	7.38	109.31
2214391	5030	42.28	23.4	14.9	7.5	60.29	19.24	11.10	7.19	115.76
2214525	3465	42.23	22.4	16.8	8.1	63.30	18.29	8.71	7.49	110.46
2214540	5030	42.75	23.5	14.4	10	59.09	18.25	13.57	6.84	119.52
2214621	5020	44.47	20	12.7	7.6	62.63	18.94	9.16	7.26	112.04
2214764	5020	46.43	18.8	6	7.2	64.49	18.06	8.51	6.95	110.40
2214784	1	45.91	19.1	10.4	10.8	62.69	19.89	8.61	6.81	112.27
2214896	5020	45.36	21	6	6.3	65.76	17.12	8.25	6.91	109.18
2215232	5030	44.15	20.5	10	7.1	62.39	17.85	10.34	7.29	113.12
2215378	5020	45.84	20	6.4	8.3	64.64	17.16	9.19	6.95	110.80
2215460	1	46.36	20.2	2.5	12.2	64.50	18.51	8.27	6.62	110.64
2215546	5020	43.31	21.2	20.4	8.8	62.29	18.26	10.20	7.09	113.41
2215595	5020	45.51	19.6	5.6	8	63.34	18.33	9.21	7.11	111.73
2215626	1	46.77	18.1	20.5	8.2	61.70	19.40	9.76	6.77	113.85
2215865	7145	48.87	17.4	0.9	6.5	62.04	20.10	8.83	7.13	112.57
2216001	7145	47.82	17.8	3.8	5.4	63.33	19.59	7.95	7.16	110.54
2216349	7145	45.34	19.2	10.1	8.1	60.77	21.05	8.78	7.36	113.08
2216390	5020	46.81	18.9	8.6	8.7	63.98	18.13	9.02	6.94	111.38
2216417	1	46.72	18.5	9.8	10.9	64.10	19.02	8.01	6.83	110.42
2216737	5020	47.46	17.7	8.7	7.5	64.68	17.60	8.75	7.09	110.31
2217065	7145	42.11	23.1	0	8.3	62.36	19.93	7.89	7.80	110.19
2217183	5020	44.33	19.7	13	10.3	62.59	18.93	9.23	7.22	112.20
2217264	5020	43.72	21	12.6	9.5	63.03	19.02	8.89	7.01	111.85
2217272	7145	46.73	18.8	3.6	6.6	61.53	20.75	8.69	7.05	112.96
2217767	5020	46.59	18.6	8.8	8.6	63.93	17.88	9.24	6.96	111.52
2217885	7145	45.23	20.7	7	7.4	63.44	18.99	8.14	7.36	110.17
2218039	5020	41.67	22	17.6	6.9	61.41	19.69	9.48	7.25	113.23
2218219	5020	47.31	17.6	9.5	7.8	63.49	18.24	9.22	7.10	111.68
2218237	5030	43.99	20.1	9	6.9	63.57	17.94	8.94	7.61	110.50
2218349	5020	44.37	20.7	12	7.9	63.31	18.04	9.49	7.09	111.97
2218606	1	44.90	20.9	7.2	8.9	62.43	19.82	8.86	6.72	112.67
2218656	1	47.98	18.4	0.2	6.8	64.34	18.72	8.13	6.82	110.40
2218675	7145	46.42	20.2	10.3	5.9	62.72	19.76	8.37	7.13	111.44
2218789	5020	41.18	23.6	13.1	10.8	61.69	18.69	10.51	6.87	114.52
2219190	5030	43.19	21	6.5	8.7	61.89	19.51	9.22	7.31	112.60
2219203	5020	46.58	18.3	15.8	9.5	63.71	18.37	8.93	7.07	111.32
2219259	7145	42.10	22.6	7.2	9.1	62.38	20.42	7.62	7.46	110.42
2219266	7145	43.30	22.4	10.1	7.9	63.12	19.78	7.83	7.23	110.44
2219268	5030	43.57	20.6	8.3	8.6	62.66	18.45	9.63	7.22	112.48
2219278	5030	42.84	21.2	10.9	8.8	62.48	18.67	9.54	7.27	112.47
2219372	1	45.54	21.7	6.7	9.3	64.01	18.46	8.61	6.67	111.11
2219866	5020	43.68	22.1	8.5	9.4	63.51	17.81	9.37	7.18	111.50
2220033	5020	48.00	17	8	8.3	64.56	17.84	8.65	7.07	110.37
2220429	5020	44.90	21.2	12	8.8	64.05	17.26	9.48	7.15	111.22

2220829	5020	44.99	19.9	7.1	7.1	65.14	17.43	8.04	7.39	108.65
2221051	5020	46.95	18.1	6.9	7.7	64.59	17.56	8.85	7.08	110.45
2221214	5030	44.83	18.5	9.2	8.7	62.34	19.58	8.85	7.32	112.01
2221324	3465	47.39	18.2	13.8	9.3	64.33	17.78	8.77	7.12	110.44
2221785	5020	44.67	20.7	6.8	12	63.12	17.77	10.30	6.72	113.51
2221903	1841	44.93	21.5	24.2	8.3	57.95	20.45	12.25	6.80	119.10
2221908	5020	47.53	18	4.7	7.5	64.77	17.28	8.85	7.16	110.13
2221976	5020	45.48	19	10.9	6.5	62.52	18.71	9.60	7.14	112.71
2222095	1841	44.93	20.3	20.5	7.3	60.46	19.97	10.21	7.14	114.85
2222161	5020	46.54	18.5	7.9	8.8	64.34	17.70	8.91	7.08	110.68
2222332	5020	49.59	14.9	4.8	6.2	64.62	17.76	8.63	7.22	110.14
2222445	3465	45.67	20.3	19.2	9	62.89	17.65	10.38	6.88	113.36
2222447	5020	46.06	19.8	16.2	7.9	64.58	18.06	8.50	6.99	110.38
2222688	1841	43.96	22.6	13	8.7	63.62	18.00	9.12	7.17	111.20
2222748	5030	42.15	21.1	16	10.6	61.09	18.63	10.56	7.55	113.96
2223348	7145	45.23	20.6	12.1	8.5	62.56	19.47	8.34	7.36	110.91
2223522	1	47.41	19.2	5	5.6	64.00	18.80	8.43	6.75	111.03
2223689	3465	45.78	18.3	14.3	7.9	62.97	18.31	9.15	7.46	111.26
2224108	5020	44.76	19.8	10.5	6.2	63.32	18.32	9.08	7.27	111.35
2224132	5030	44.82	19.9	9.8	7.4	62.64	17.49	10.51	7.24	113.15
2224172	1	43.70	22.9	9.5	10.9	63.30	18.78	8.74	6.85	111.45
2224303	1	44.80	20.4	19.8	11	63.53	18.88	8.42	7.02	110.84
2224623	5020	43.68	20.9	9.5	8.2	62.79	18.67	9.13	7.29	111.71
2224870	7145	44.06	21	15.4	8.3	61.15	20.77	8.49	7.46	112.26
2224876	3465	43.47	21.6	12.7	9	62.50	19.57	8.58	7.24	111.57
2224897	5030	43.74	21.5	13.2	8.2	61.76	18.51	10.47	7.14	114.05
2225097	7145	42.59	23.4	1.9	6.6	64.21	18.35	7.60	7.79	108.30
2225189	5020	43.39	20.7	15.7	10.9	63.10	19.33	8.46	7.11	111.28
2225277	7145	45.69	18.6	5.7	7.1	62.27	19.85	8.31	7.45	111.13
2225509	5030	42.90	22.2	8.7	8.1	62.02	18.67	10.01	7.19	113.36
2225518	5030	45.11	19.1	8.6	7.8	61.70	19.19	9.66	7.41	113.00
2225850	7145	44.56	21.4	7.9	9.1	64.36	18.59	7.78	7.22	109.32
2225853	1841	46.99	18.6	12.3	8.3	65.85	16.17	9.04	6.99	109.63
2225884	1841	45.65	20	8.3	7.7	62.23	19.74	8.95	7.03	112.53
2226344	5020	45.85	19.7	10.9	9.2	64.03	17.83	9.19	6.97	111.37
2226384	5020	44.42	21.6	7.4	8.5	63.12	17.75	10.05	6.94	112.82
2226410	5030	44.21	19.9	11.1	9.4	61.60	18.42	10.51	7.38	113.85
2226415	7145	43.60	23.8	8.9	7.7	61.26	18.95	10.66	6.88	114.95
2226462	1841	46.25	18.9	11.4	7.9	62.02	19.62	8.99	7.24	112.31
2226520	5020	42.70	23.3	10.7	9.6	64.45	17.59	8.62	7.24	109.93
2226624	7145	43.47	21	7.1	7.3	62.16	20.55	7.83	7.45	110.91
2226846	5020	41.33	23.2	23.8	10.8	63.05	18.86	8.64	7.39	110.95
2227134	5020	46.10	18.7	20.3	8.3	63.81	17.84	9.37	6.96	111.71
2227411	7145	43.41	21.8	11.6	7.4	60.21	21.53	8.63	7.45	112.69
2227489	5030	41.60	23.1	10.1	8.2	62.17	18.46	9.83	7.34	112.72
2227490	5030	40.85	23.5	10.9	8	61.12	19.31	9.93	7.34	113.62
2227550	5020	47.48	17.5	12.4	8.4	64.45	17.94	8.47	7.23	110.00
2227576	7145	45.80	19.9	11.1	6.9	63.11	19.20	8.44	7.18	111.04
2228740	5020	46.21	20.4	14	8.1	63.31	18.44	9.41	6.82	112.43
2228918	1841	42.69	23.6	20.1	10.6	59.86	20.75	10.20	6.94	115.69
2230066	5020	45.60	20.7	11.8	9.9	66.07	16.82	8.23	6.89	108.89
2230132	3465	44.51	20.4	10.6	8.3	64.10	18.01	8.60	7.20	110.28
2230183	3465	42.97	21.2	21.7	5.7	63.64	18.06	8.58	7.47	110.00
2231323	5020	46.62	18.8	6.5	9.3	63.86	17.55	9.83	6.74	112.46
2231342	5020	41.71	21	12.9	8.3	63.12	19.60	7.52	7.82	109.24

2231675	5020	45.38	19.6	13	7.5	62.40	19.00	9.56	7.04	113.00
2231820	5030	44.16	21.7	4.4	8.6	62.72	16.88	11.01	7.25	113.48

Key:
Chloro = Chlorophyll
Glucos = Glucosinolates
C181 = Oleic acid
C182 = Linoleic acid
C183 = Linolenic acid
Sats = Total saturated fatty acids
IV = Iodine value
Variety 1 = SP Banner

Table A4.3 Quality of western Canadian canola for the 2009 Harvest Survey dataset.

Sample	Variety	Oil	Protein	Chloro	Glucos	C181	C182	C183	SATS	IV
2305273	5020	47.50	17.8	16.7	11.3	61.69	19.05	10.67	6.67	115.33
2305502	5020	48.41	17.2	12.7	8.2	65.25	16.88	9.33	6.72	111.07
2305836	5020	44.5	18.7	13.7	9.3	62.75	19.30	8.85	7.15	111.94
2306026	7145	44.9	21.1	19.4	9.2	60.62	20.29	10.13	6.83	115.25
2306046	1	46.82	19.3	9.6	5.3	62.04	19.85	9.67	6.39	114.46
2306431	3465	46.27	18.2	18.5	8.3	63.90	18.09	9.14	6.90	111.54
2306592	7145	42.50	24.3	8.1	10.4	61.73	19.95	9.18	7.02	113.14
2306723	5030	43.17	21.9	17.1	8.7	61.03	18.46	11.66	6.79	116.45
2307042	5020	47.27	17.2	12.3	10.3	63.06	18.52	9.65	6.84	112.93
2307420	5030	43.11	21.4	12.4	7.8	62.10	17.90	11.11	6.83	114.92
2308671	5030	42.36	22.6	16.8	7.6	61.25	18.43	11.17	7.03	115.33
2309351	7145	40.83	21.9	13.3	9.7	57.92	23.10	8.96	7.71	114.82
2309881	5020	48.42	16.2	12.7	9.2	62.91	18.32	9.98	6.90	113.30
2310003	5020	44.34	20.6	8.5	9.5	62.01	18.41	10.97	6.45	115.47
2310308	3465	47.07	17.2	13.4	7.9	62.14	18.77	10.09	7.04	113.72
2310311	7145	46.70	19.5	8.7	11.3	62.03	19.87	9.33	6.76	113.56
2310318	7145	48.79	16.9	8.4	11.7	59.99	20.96	10.36	6.80	116.33
2310334	5020	43.00	22.9	17.9	9.6	62.56	18.48	10.03	6.84	113.55
2310475	5020	44.08	21.9	14.7	10.4	62.89	18.47	9.85	6.74	113.32
2310530	7145	45.66	20.7	12.8	9.5	62.35	19.28	9.44	6.86	113.16
2310745	7145	45.50	20.2	7.1	8.5	61.89	19.92	9.44	6.73	113.81
2310922	5030	46.91	17.7	9.3	7.7	63.24	17.17	10.64	7.03	113.33
2311728	5020	47.46	17.3	12.4	9.2	62.15	19.02	10.16	6.74	114.35
2312006	5030	42.15	20.9	11.9	7.8	59.98	19.77	11.06	7.14	116.22
2312092	3465	47.05	17.7	23	9.7	62.68	18.43	10.29	6.71	114.04
2312239	5020	46.59	18.8	10.6	8	63.92	17.57	9.74	6.81	112.28
2312691	1	43.94	21.3	10.9	8.9	61.76	20.23	9.07	6.90	113.30
2312841	7145	46.03	19.9	17.3	10.7	61.69	20.20	9.00	7.02	113.01
2312997	5020	41.90	20.2	17.1	10.9	58.74	21.48	10.38	7.21	116.41
2313752	5030	40.55	22.2	11.2	12.8	59.03	20.40	11.17	7.40	116.76
2313938	7145	48.45	17.5	11.7	8.1	61.21	20.27	9.83	6.68	114.85
2314707	5020	46.43	18.7	19.5	10.8	60.99	18.80	11.22	6.99	115.81
2314754	5020	42.62	21.7	25.7	10.3	58.28	21.18	11.23	7.06	117.79
2314948	1	47.51	17.1	13.1	7.8	61.77	19.82	9.93	6.57	114.76
2314987	3465	45.10	19.7	12.8	9.2	63.41	17.86	9.87	6.69	112.81
2315004	7145	46.9	18.2	3.7	8.1	60.97	20.67	9.35	7.01	114.07

2315005	7145	46.78	18.1	4.4	7.8	61.20	20.45	9.29	7.06	113.73
2316329	7145	48.04	17.2	6.2	7.2	60.26	21.41	9.41	6.88	114.92
2317427	5030	45.43	19.3	10.1	8.2	61.86	18.05	11.32	6.82	115.47
2317431	5030	46.79	16.7	13.6	8.4	61.97	17.95	11.15	7.04	114.91
2317913	5030	42.67	22.4	7.5	8.4	62.57	17.85	10.52	7.03	113.70
2318617	5020	44.28	22	3.2	11.6	61.15	19.00	11.07	6.60	116.03
2319141	1	46.04	20.3	14.6	8.2	61.28	19.76	10.14	6.65	114.98
2319495	1	48.98	16.7	3.1	7.9	62.23	19.46	9.85	6.44	114.39
2319568	5020	46.11	17.2	11.9	7.4	60.90	19.78	10.35	7.01	115.10
2320620	7145	45.81	20.2	11.7	7.4	61.74	20.28	8.94	6.92	113.07
2320738	5020	41.80	20.8	24.6	12.8	59.19	21.34	9.70	7.58	114.80
2320766	5020	44.70	21.1	17.3	9	59.78	19.72	11.57	6.79	117.36
2320809	3465	47.85	17.2	15	7.9	64.40	17.32	9.24	7.03	110.94
2320861	7145	47.50	18.9	7.5	9.7	62.29	19.28	9.80	6.68	113.93
2321254	7145	47.26	20.4	25.4	12.1	63.12	18.56	9.79	6.51	113.48
2322750	1	45.91	20	12.7	10.7	61.42	19.76	10.40	6.45	115.63
2322751	1	47.70	17	15.4	11	61.52	19.75	10.18	6.67	115.05
2323532	5030	40.51	21.3	14.8	9.4	60.95	19.34	9.78	7.84	112.98
2324245	5030	44.61	19	13	9.5	60.87	18.64	11.50	6.95	116.14
2325559	5020	46.25	18.2	16.6	7.8	62.18	18.94	9.97	6.93	113.78
2328373	5020	46.44	19.6	9.9	10.2	63.20	18.07	10.18	6.55	113.72
2330857	5030	41.96	25.2	7.7	11.2	60.63	18.41	12.41	6.43	118.02
2330906	5020	44.66	20	7.2	11.8	61.17	18.35	11.84	6.51	116.90
2331595	5020	44.07	21.7	17.6	12.4	61.89	18.33	11.46	6.18	116.52
2331783	5020	42.5	20	15	8.1	59.24	20.83	10.48	7.25	116.02

Key:
Chloro = Chlorophyll
Glucos = Glucosinolates
C181 = Oleic acid
C182 = Linoleic acid
C183 = Linolenic acid
Sats = Total saturated fatty acids
IV = Iodine value
Variety 1 = SP Banner

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