THE EFFECT OF CANOLA CULTIVAR ON WATER EXTRACTION AND NITROGEN AND SULPHUR UPTAKE

BY

MARLA RAE RIEKMAN

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Soil Science
University of Manitoba
Winnipeg, MB

0-494-08946-6

Your file *Votre référence*
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ABSTRACT

Riekman, Marla Rae. M. Sc., The University of Manitoba, October, 2005. The Effect of Canola Cultivar on Water Extraction and Nitrogen and Sulphur Uptake. Professor, Dr. Donald N. Flaten.

The objective of this study was to assess the mechanism that leads to enhanced uptake of N and S by a hybrid canola cultivar. Two canola cultivars, one hybrid (45H21) and one open-pollinated (Conquest) were grown at a single location near Rosebank, MB during the 2003 growing season to study the impact of canola cultivar and S fertilization on the uptake of water, N and S from the soil. The experimental design was a Randomized Complete Block where each cultivar was exposed to three fertilizer treatments: a control, 160 kg N ha^{-1}: 0 kg S ha^{-1}, and 160 kg N ha^{-1}: 27 kg S ha^{-1}. Soil and plant N and S concentrations were measured at midseason and maturity to determine the uptake of N and S by each cultivar. Soil moisture content was monitored throughout the growing season to study the activity of the canola roots. As well, soil cores were removed at midseason to determine the difference in rooting depth by each cultivar. The year following the canola crop experiment, AC Barrie spring wheat was seeded to the canola stubble without N fertilizer to study the effect of N and S uptake by each canola cultivar on a subsequent crop.

Biomass was greatest for the hybrid canola cultivar at both sample periods. The concentration of N and S in the canola tissue at midseason was higher in the open-pollinated cultivar, which offset the biomass difference; therefore, the total N and S

accumulated by each cultivar was not statistically different. At maturity, the difference in tissue concentrations was seen for S only. The addition of fertilizer caused an increase in biomass production as well as a significant increase in N accumulation at midseason and maturity, and an increase in S accumulation at maturity only. Seed yield was highest for the hybrid cultivar and increased with fertilizer application for both cultivars. There was no interaction between cultivar and fertilizer treatment, indicating that each cultivar responded similarly to fertilizer addition.

There was no significant difference in rooting depth between the two cultivars; however, the hybrid cultivar removed 58 mm more water than the open-pollinated cultivar over the 10 to 110 cm soil depth during the growing season, for the N plus S fertilizer treatment only. The difference in root activity may be attributed to the greater biomass of the hybrid canola, leading to higher rates of transpiration. Water use efficiency (WUE) was greater for the hybrid canola cultivar due primarily to the higher seed yield of this cultivar.

The biomass accumulated by the wheat seeded onto the open-pollinated canola stubble was numerically greater than that on the hybrid stubble, but this was significant for the midseason sampling period only. Biomass accumulation and total recovery (biomass and soil) of N and S by the wheat seeded onto the open-pollinated stubble was numerically greater, but not significantly so. Again, there was no interaction between cultivar and fertilizer treatment on either accumulation or recovery of N and S by the wheat crop.

FOREWORD

This thesis has been prepared in the traditional format in adherence with the guidelines established by the Department of Soil Science. The reference style of the Canadian Journal of Soil Science has been used throughout this document. Only one site year of data was analyzed for each experiment in this study. A second site year was established for the canola crop experiments; however, due to poor weather conditions, soil conditions and a loss of treatments, the data from this site year is not included in this thesis.

As well, a wheat crop experiment was seeded in 2003 to the Westco N:S ratio plots from 2002. The previous canola experiment included three canola cultivars, two hybrid and one open-pollinated and two fertilizer treatments, a control and the 160 kg N ha^{-1}: 27 kg S ha^{-1} treatment. Therefore, since the canola cultivar and fertilizer treatments that preceded the 2003 wheat experiment were different than those for the 2004 wheat, we chose the latter portion of the experiment in order to simplify the analysis of the follow crop experiment.

ACKNOWLEDGEMENTS

I would like to thank the following institutions and individuals that helped to make this research project possible:

Thank you to Western Cooperative Fertilizers Inc. (Westco) for both funding this project and providing plot maintenance. The technical assistance of Don Poisson, Tony Stonehouse, Shaan Tsai, and Angela Gesselman was greatly appreciated. Other funding, as an Industrial Post-Graduate Scholarship, was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC).

Special thanks to my advisor, Dr. Don Flaten, for your endless patience, kindness and support. Your motivation and sense of humour kept me going, even through the most frustrating moments...of which there were a few! I would also like to thank the members of my examination committee for their much-needed and much-appreciated advice: Dr. Martin Entz, Department of Plant Science; Dr. Rigas Karamanos, Western Co-operative Fertilizers Inc.; and Dr. Tee Boon Goh, Department of Soil Science.

Thank you to the many students who assisted in gathering data; specifically, thanks to Myron Kroeker, Quinn Pomarenski and Philip Bock. I am grateful your positive attitude in the field, even though most days were extremely long and hot! Also, thanks to

Michelle Erb, Kelly Senkiw, Denis Trémorin and Cedric Vaissade for pitching in when extra hands were needed.

This project would not have gone so smoothly if it wasn't for the help of the office and field staff, so many thanks to Barb Finkelman, Terry Ramm, Tim Stem and Keith Bamford. As well, thanks to Sangu Angadi for his technical assistance and for patiently answering ALL of my stats questions!

Last, but in no way least, thanks to all my family and friends for their emotional support; especially, thanks to my mother for her endless patience and even more endless phone conversations!

TABLE OF CONTENTS

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

1. INTRODUCTION

Canola is a major oilseed crop for producers in Western Canada. In 2003, roughly 11.5 million acres of canola were harvested (Canola Council of Canada 2003). Of the canola acreage reported for 2003, 35 percent were hybrid varieties, up from 15 percent in 2000 (Pioneer Hi-Bred Limited 2004). Hybrid canola cultivars typically have a higher yield potential than the traditional open-pollinated varieties (Brandt et al. 2002; Karamanos et al. 2002; Van Deynze et al. 1992); therefore, they are gaining in popularity with today's producers.

Canola has been identified as being a high N-requiring crop, on average removing a total of 125 kg N ha^{-1} during the growing season (Manitoba Agriculture and Food 2001). Overall, N fertilization influences the growth and development of the crop by significantly increasing above ground plant growth (Grant and Bailey 1993) and total dry matter accumulation (Asare and Scarisbrick 1995; Hocking et al. 2002; Rathore and Manohar 1989) which, in turn, leads to greater seed yield production. Along with N, canola also has a high requirement for S to achieve maximum yield (Grant et al. 2004; Grant et al. 2003; Malhi and Gill 2002); approximately 1.5 kg of S is needed to produce 100 kg of seed (Grant and Bailey 1993). When S is limiting, especially at flowering, the result will be a loss in yield (Grant and Bailey 1993), even if visual symptoms of a deficiency are lacking (McGrath and Zhao 1996). As a result, it is important that canola fertilization practices are well-planned, so that the S requirement of the plant can be met.

A balance between N and S must be maintained in canola production, since the demand for each nutrient is high and an interaction between N and S controls the rate of uptake for each nutrient. Sulphur is a component in nitrate reductase, required for the conversion of NO_3^- to amino acids and proteins within the plant, and N is used to form ATP-sulphurylase, the enzyme responsible for sulphate assimilation (Ahmad and Abdin 2000). Therefore, if either N or S is deficient, the assimilation of the other nutrient would decrease, creating a deficiency in that nutrient as well.

The current fertilizer practices for canola production have been developed to maintain the balance of N and S for optimal yield. Agronomists recommend applying fertilizer based on an N:S ratio of 7:1 (Saskatchewan Agriculture, Food and Rural Revitalization 2003; Manitoba Agriculture, Food and Rural Initiatives 2003), as this ratio mimics the N and S uptake generally exhibited by canola (Janzen and Bettany 1984). Sulphur fertilizer is often recommended on soils that have adequate soil test S concentrations, in order to ensure high canola yields. The recommended fertilizer N:S ratio is based on research carried out on the more traditional open-pollinated varieties of canola. However, in the past few years, as hybrid canola acreage has increased, research has begun to focus on the specific fertilizer needs of these new, higher-yielding varieties. In research on the impact of fertilizer N:S ratio on hybrid and open-pollinated canola cultivars, Karamanos et al. (200) found that open-pollinated varieties tend to respond to a decrease in N:S fertilizer ratio (increase in S rate), even on soils with adequate soil test S. In contrast, hybrid cultivars have shown little to no response to fertilizer S (Karamanos et al. 2002). Deibert et al. (2002) postulated that hybrids may be more efficient at using plant-available S, as the seed of the hybrid canola in their experiment had higher S contents than that of the open-pollinated varieties.

Along with higher yields, hybrid canola cultivars typically exhibit more vigorous above ground growth than open-pollinated cultivars (Brandt et al. 2002; Harker et al. 2003; Zand and Beckie 2002). The higher biomass production may be driving the need for increased fertilizer N; however, one would also expect an increase in need for fertilizer S. It is possible that the increase in above ground biomass production may be matched by a similar increase in below ground biomass. Therefore, the hybrid canola may have an increased root number and/or be rooting deeper than open-pollinated canola, gaining greater access to the available SO_4^{2-} at depth in the soil. In essence, the hybrid cultivars may be more efficient "scavengers" of soil nutrients (Karamanos and Flore 2002; Karamanos et al. 2002) due to their ability to access more nutrients and utilize these nutrients more efficiently than traditional open-pollinated canola cultivars.

A greater uptake of N and S by hybrid canola cultivars may have an impact on the fertilizer additions required for the next growing season. For example, if hybrid canola extracts more N from the soil, then more fertilizer N may be needed to maintain the following crop. Therefore, it is important to fully understand the rates of N and S uptake by hybrid canola cultivars, as it may have an effect on future fertilization practices.

The overall objective of this project was to assess the mechanism that leads to the enhanced uptake of N and S by higher yielding canola cultivars. Specifically, the purpose was to investigate the impact of S fertilization on different canola cultivars, in terms of its effect on N and S accumulation, rooting depth and rooting activity. Water loss was used as a measure of rooting activity, as both NO_3^- and SO_4^{2-} are water soluble nutrients that move toward plant roots by mass flow. As well, wheat was seeded the following season to determine the amount of recoverable N and S remaining after growing the canola cultivars. For this study, two canola cultivars, one hybrid and one open-pollinated were utilized; however, with only one cultivar representing each type of canola, the results of these experiments may not apply to hybrid and open-pollinated cultivars, in general.

2. LITERATURE REVIEW

2.1. Nitrogen in Canola Production

Of the mineral nutrients required by plants for growth and development, nitrogen is the most important from an agricultural perspective. N is essential for the composition of amino acids and proteins and plays an important role in the generation of carbohydrates from light energy via photosynthesis (Havlin et al. 1999). Therefore, it is required by plants in amounts greater than any other nutrient (Taiz and Zeiger 2002). The use of N fertilization practices in canola production causes increases in seed and oil yields, while also increasing the overall growth of the plant.

2.1.1. Physiological and Metabolic Roles of Nitrogen

Nitrogen is an essential nutrient for plant growth, required for the composition of many proteins, amino acids, enzymes and chlorophyll (Grant and Bailey 1993; Havlin et al. 1999; Taiz and Zeiger 2002; Olson and Kurtz 1982). Upon assimilation into amino acids, N is incorporated into proteins that become the building blocks for chloroplasts, mitochondria and other biochemically-active structures (Havlin et al. 1999). Therefore, the amount of N available to the plant will determine the rate of photosynthesis and the amount of carbohydrates produced. Adequate N supplies will also stimulate the formation of proteins from these carbohydrates (Havlin et al. 1999).

2.1.2. Nitrogen Uptake and Distribution in Canola, Rapeseed and Mustard

Nitrogen can be absorbed by the plant in the form of ammonium, NH_4^+, or nitrate, NO_3^- (Havlin et al. 1999; Taiz and Zeiger 2002; Olson and Kurtz 1982). Upon absorption into the roots, NH_4^+ is quickly assimilated into amino acids, because high levels of NH_4^+ can be toxic to plants. The NO_3^- that is absorbed by plant roots is reduced to nitrite, NO_2^-, via the nitrate reductase enzyme. The NO_2^- generated by this process is then transported to either the chloroplasts in leaves or the plastids in roots where it is further reduced to NH_4^+. The NH_4^+ is quickly converted into amino acids, in order to avoid NH_4^+ toxicity (Taiz and Zeiger 2002).

Due to the mobility of N in the plant, N deficiency symptoms are observed in the older leaves (Havlin et al. 1999). If N is limiting for crop growth and development, N will be removed from the old leaves and used for new tissue development. Most of the N accumulated by canola is taken up prior to anthesis (Hocking and Stapper 2001). As the plant matures, the concentration of N in the plant tissue decreases and seed N concentrations increase (Rood et al. 1984). Between anthesis and maturity, canola plants can lose approximately 35% of total N in the shoots (Hocking et al. 2002). Even with adequate N supply, movement of N from old tissue is important for reproductive development, as the translocated N is used to develop buds, pods and seeds.

2.1.3. Distribution and Plant Availability of Soil Nitrogen

Of the two forms of N available for plant uptake, the most commonly absorbed is NO_3^-. NO_3^- is a water soluble nutrient; therefore, it moves freely with water through the soil

(Hillel 1998). This is due to the negative charge of the ion, which is repelled by the net negative charge exhibited by most soils. As a result, NO_3^- is not adsorbed to soil surfaces. Soil NO_3^- concentration fluctuates throughout the growing season, unlike exchangeable NH_4-N, which remains low and constant (Campbell and Biederbeck 1982). For this reason, NO_3-N is most often examined in studies of soil N levels.

The distribution of nitrate in the soil is extremely variable, depending on soil properties, such as texture, which affects the rate of water movement through the soil and landscape position, which affects transfer of water from one area of a field to another. Soil nitrate concentrations will also differ from one area to another due to environmental influences, such as the amount of N added by fertilizer or the recycling of dead plant material. As well, the amount of moisture that falls on a field, as rain or irrigation water, will affect how deeply the nitrate penetrates the soil.

The majority of N extracted by plants as NO_3^- is usually from the upper surface of the soil profile (Hocking et al. 2002; Rood et al. 1984). Hocking et al. (2002) reported that canola and Indian mustard removed a significant amount of mineral-N from the 0 to 50 cm depth. As a result of the higher root extraction of N in the upper soil depth, any N that moves below this depth may accumulate lower in the soil profile. Research by Rood et al. (1984) found an increase in NO_3-N concentration at the 33 to 66 cm and 66 to 100 cm depths mid-way through the growing season, indicating that NO_3^- was being leached down through the profile from the shallow depths once the crop's demand for soil N had decreased. The density of roots at the 60 to 120 cm depth is low and active extraction of water and nutrients occurs for only a short time during the growing season (Campbell and Biederbeck 1982). The low root activity at greater soil depths allows for NO_3^- to leach below the rooting zone; therefore, concentrations of NO_3^- may be very high deep in the soil profile.

2.1.4. Effect of Nitrogen Fertilization on Canola, Rapeseed and Mustard Yield and Quality

A typical canola crop in Manitoba will remove a total of 125 kg N ha^{-1} (Manitoba Agriculture and Food 2001); therefore, it is recommended that 78 to 100 kg N ha^{-1} be applied when growing canola on most Manitoba soils. Due to their high N requirement, the use of N fertilizer in canola, rapeseed and mustard production can significantly increase overall seed yield (Allen and Morgan 1972; Asare and Scarisbrick 1995; Holmes and Ainsley 1977; Mason and Brennan 1998; Ramsay and Callinan 1994; Rathore and Manohar 1989; Taylor et al. 1991; Zhao et al. 1993) by influencing the growth and development of the crop. A greater number of branches, buds, and flowers per plant, in combination with more vigorous above-ground plant growth cause an increase in seed production (Grant and Bailey 1993). Specifically, higher yields with N application are due to an increase in the number of pods per plant (Allen and Morgan 1972; Asare and Scarisbrick 1995; Zhao et al. 1993). Zhao et al. (1993) reported that the greater seed yield in N fertilized rapeseed was due primarily to the higher number of potential and fertile pods on each plant. Asare and Scarisbrick (1995) determined that the number of pods was higher on the terminal raceme of the N fertilized rapeseed plants compared to the unfertilized plants, leading to increased seed yields. Other research has also found that a significant increase in the primary and secondary branches per plant may occur with higher N application rates (Rathore and Manohar 1989). A greater number of branches and pods allow canola and rapeseed plants to produce a higher number of seeds.

The application of N fertilizer may also affect the weight of each seed; however, research has shown this to be a variable effect. Zhao et al. (1993) found N application to increase the thousand kernel seed weight at one of two experimental sites and decrease seed weight at the other. In other studies, N fertilizer caused a small increase in seed weight (Allen and Morgan 1972; Asare and Scarisbrick 1995). Variability is also a factor in the measurement of seed number per pod. Zhao et al. (1993) observed an overall decrease in the number of seeds per pod, whereas Asare and Scarisbrick (1995) found no effect of N on seed number per pod.

As well as affecting seed yield, the application of N fertilizer also has an effect on the quality of seed produced. The protein content of canola and rapeseed has been shown to increase with application of N fertilizer (Asare and Scarisbrick 1995; Mason and Brennan 1998; Ramsay and Callinan 1994; Zhao et al. 1993). In general, the oil content of the seed will decrease with increasing N rate, resulting in an inverse relationship between protein and oil content in response to N application (Allen and Morgan 1972; Asare and Scarisbrick 1995; Hocking et al. 2002; Hocking et al. 1997; Holmes and Ainsley 1977; Mason and Brennan 1998; Ramsay and Callinan 1994; Taylor et al. 1991; Zhao et al. 1993). However, as with the variability in canola and rapeseed weight response, the effect that N rate has on oil content also shows some variable results. In some of the experiments, the reduction in oil content was not statistically significant at all sites (Holmes and Ainsley 1977; Mason and Brennan 1998). Ramsey and Callinan (1994) reported that one of their experimental sites had an overall increase in seed protein of canola with addition of N fertilizer. The particular site had very low concentrations of soil N; therefore, severe N deficiencies would have caused very low yields in the control treatment, resulting in an unusually large increase in seed yield due to N fertilization. The low soil N concentration may explain the atypical response of seed oil content to N application rate. Even with the decrease in seed oil content, the total oil yield of canola and rapeseed on a per hectare basis increases with N rate, due to the overall increase in seed yield (Allen and Morgan 1972; Holmes and Ainsley 1977; Taylor et al. 1991).

Along with increasing seed and oil yield, N fertilization may also increase the total dry matter produced by canola, rapeseed and mustard plants (Asare and Scarisbrick 1995; Hocking et al. 2002; Rathore and Manohar 1989). Allen and Morgan (1972) reported that the leaf area index of oilseed rape was greater when the crop was fertilized with N. As well, addition of N has been shown to cause a significant increase in canola straw yield (Nuttall et al. 1992).

The increase in leaf area due to N fertilization is an important factor because it may allow for greater supply of N to the seed during development (Allen and Morgan 1972). Asare and Scarisbrick (1995) observed a lengthened "green-time" with N fertilization, where the fertilized rapeseed plants senesced later than the non-fertilized plants. This allows the plant to assimilate more N for seed filling, resulting in higher yields. Similar findings were reported by Wright et al. (1988) in Australia, where the addition of fertilizer N delayed crop maturity, allowing for further N uptake, thus increasing canola yield.

2.2. Sulphur in Canola Production

Sulphur is the 13th most abundant element found in the crust of the earth (Havlin et al. 1999) and the fourth most important nutrient for crop production (Grant and Bailey 1993). S is especially important in canola nutrition as canola has a high requirement for S-containing amino acids, such as cysteine and methionine. S deficiencies have the greatest effect on the reproductive organs of canola, causing major decreases in yield, as opposed to N deficiencies which have a greater effect on dry matter production (Fismes et al. 2000; Singh and Nad 2000). However, with proper S fertilization practices, producers can achieve high yielding, high quality canola, even on soils that are naturally deficient in S.

2.2.1. Physiological and Metabolic Roles of Sulphur

S is an essential nutrient in plant metabolism as it is a major constituent of the amino acids cystine, cysteine and methionine (Grant and Bailey 1993; Thompson et al. 1986; Von Uexkull 1986). Sulphate, SO_4^{2-}, is reduced and incorporated into cysteine in the chloroplasts, which may then be incorporated in methionine (Taiz and Zeiger 2002; Thompson et al. 1986). Cysteine and methionine may also be synthesized into metabolites such as coenzyme A, biotin, and thiamin, important components in plant metabolism although they are present in the plant in lesser amounts (Thompson et al. 1986). Sulphur plays a role in the synthesis of chlorophyll (Grant and Bailey 1993), aids in the function of nitrate reductase which converts NO_3–N into amino acids in the plant (Ahmad and Abdin 2000) and exists in proteins as iron-sulphide bonds that function as electron carriers (Thompson et al. 1986).

In plants of the family *Cruciferae*, S is a major component of the mustard oils, or glucosinolates, which are characteristic of this family (Von Uexkull 1986). Glucosinolates are volatile oils that accumulate in cruciferous plants (Grant and Bailey 1993) as a defence mechanism. High concentrations of glucosinolates decrease the palatability of the crop, which in turn affects canola meal quality. Therefore, canola is now bred to have low glucosinolate content (Grant and Bailey 1993; Nuttall et al. 1987) to increase the quality of the seed.

2.2.2. Sulphur Uptake and Distribution in Canola, Rapeseed and Mustard

The primary form of S that is taken up by plants is as a divalent anion, SO_4^{2-} (Grant and Bailey 1993; Scherer 2001). Sulphate uptake primarily occurs in the root hair region using an H^+/SO_4^{2-} cotransport system (Scherer 2001; Taiz and Zeiger 2002). Smaller quantities of S can also be absorbed by the plant through stomates on the underside of the leaf, from atmospheric SO_4^{2-} concentrations (Scherer 2001).

Upon absorption by the plant roots, SO_4^{2-} is transported to the leaf by the xylem (Blake-Kalff et al. 1998; Scherer 2001). The transport process involves a number of transmembrane and long-distance transport steps within the xylem itself (Scherer 2001). As the newest leaves develop, they become strong S-sinks (Blake-Kalff et al. 1998) as they are the primary location of SO_4^{2-} assimilation (Taiz and Zeiger 2002). However, after the leaves have fully expanded, they exhibit a net loss of S (Blake-Kalff et al. 1998) due to the movement of assimilates toward the shoot apex for new tissue development (Taiz and Zeiger 2002). The requirement of canola for S becomes highest at the flowering and bud stage (Grant and Bailey 1993), as the assimilated S is utilized for seed and pod formation.

The concentration of S in the plant is temporally variable between growth stages and spatially variable between different plant tissues. Generally, the highest concentrations are seen in the leaf tissue, as opposed to the stems (McGrath and Zhao 1996). However, there is variability in the form of S found within the different leaves of the plant. For example, in oilseed rape leaves, Blake-Kalff et al. (1998) found that 42% of S in the youngest leaves was accumulated as SO_4^{2-}, as compared to 70% to 90% of S as SO_4^{2-} in the older leaves.

2.2.3. Distribution and Plant Availability of Soil Sulphates

In the soil, S occurs in both organic and inorganic forms, the organic form of S being the most abundant in noncalcareous surface soils, composing nearly 90% of total S (Havlin et al. 1999). The inorganic S content of well-drained, aerated soils is generally composed of water-soluble SO_4^{2-} and SO_4^{2-} absorbed to clays, and Fe and Al oxides (Trudinger 1986). In calcareous soils, SO_4^{2-} may be coprecipitated with calcium to form $CaSO_4$ (Trudinger 1986), an abundant compound in many Manitoba soils.

Research on the S status of 17 soils collected from the eastern Canadian Prairies found that total S content (SO_4^{2-} plus organic S) decreases with sample depth (Bailey 1985). For the 17 soils that were sampled, the total S content ranged from 120 to 1110 mg S kg^{-1} in the 0 to 15 cm depth, from 70 to 770 mg S kg^{-1} in the 15 to 30 cm depth and from 40 to 490 mg S kg^{-1} in the 30 to 60 cm depth. Bailey found that the high total S content of the soil was related to both the organic C and total N contents of the soil. Generally, soils with lower C:N and N:S ratios have a higher potential to mineralize organic sulphur for plant uptake. Lower C:N and N:S ratios are indicative of higher biological activity and mineralization, which leads to oxidation of organic S to the SO_4^{2-} form.

The oxidation of organic S is important for increasing the S-supplying power of the soil because plants absorb S as SO_4^{2-}. Even so, the SO_4^{2-} content as a percentage of total S, is typically low in the soil. Bailey (1985) found the percentage of SO_4^{2-} in surface soils of the eastern Canadian Prairies to range from 0.9% to 5.3%, while SO_4^{2-} at the deeper depths ranges from 1.2% to 6.0% and 1.3% to 4.7% in the 15 to 30cm and 30 to 60cm depths, respectively.

Crops, such as rapeseed or canola that require high amounts of S, rely heavily on the availability of subsoil sulphate. Rapeseed is able to utilize SO_4^{2-} extracted from soil depths of up to 72 cm (Bole and Pittman 1984). The root system of oilseed rape consists of a high number of fine roots with a large amount of root hairs, allowing the plant greater access to the available soil SO_4^{2-} (Donald et al. 1993). S deficiency symptoms may be seen in canola plants early during the growing season when S is not readily available in the upper soil depths. However, as the crop matures, roots may reach a source of S in the subsoil, allowing canola to recover from those deficiency symptoms (Bole and Pittman 1984).

2.2.4. Effect of Sulphur Deficiency on Canola Growth, Development and Yield

Sulphur deficiencies have been reported in Western Canadian soils; however, there is much variability in their occurrence. Soils that are most likely to be S deficient are those that are well-drained and coarse-textured, such as the Gray Luvisolic and Eutric Brunisolic soils (Beaton and Soper 1986). Deficiencies may be further exacerbated by the consistent removal of S by crops, in the absence of fertilizer S additions. As well, as plant tissue decays, very small amounts of organic volatile S-containing compounds such as methyl disulphide are released into the atmosphere. Erosion of soil and leaching of SO_4^{2-} through the soil profile are other pathways of S loss which may cause S deficiencies, even in soil types that are normally S sufficient (Tisdale et al. 1986). Deficiencies in S are not common in soils that are formed under grassland vegetation, such as the Dark Brown and Brown Chernozems, where there is less precipitation, higher rates of evaporation and a higher amount of $CaSO_4$ in the subsoil (Beaton and Soper 1986).

Sulphur deficiency is most often seen during the bud and flowering stages. The deficiency is observed first as a general yellowing of the younger parts of the plant, due to a decrease in chlorophyll synthesis. As the canola matures, those plants that are S-deficient exhibit smaller, paler yellow flowers (McGrath and Zhao 1996). The youngest plant tissue is affected because the main role of S is for protein structure (Grant and Bailey 1993), so S is not available for mobilization to the affected area. When a plant lacks S for a long period of time, SO_4^{2-} stored in the vacuoles is released for new growth; however, this release is slow and cannot support the generation of new tissue (Blake-Kalff et al. 1998). Severe S deficiency results in cupping of the leaves, purpling of the stems and pods, delayed maturity and poor pod filling. Pod filling is especially affected at the top of the plant (Grant and Bailey 1993).

Due to poor remobilization of S within the plant, canola yields may be significantly reduced by S deficiency, even if the visual signs of a deficiency are lacking (Grant and Bailey 1993; Manitoba Agriculture, Food and Rural Initiatives 2003). Options for determining S deficiencies include testing the plant tissue during the growing season for total S concentrations and also determining the N:S ratio of the plant. The optimal time for diagnosing an S deficiency using the concentration of S in leaves is at early flowering (McGrath and Zhao 1996). If total S at flowering is less than 0.2%, then the concentration of S in the plant is considered low. A tissue content of 0.2%-0.25% of total S is considered marginal and anything over 1% is excessive. If both N and S contents are being measured, an N:S ratio of 12 is needed to achieve maximum yield (Grant and Bailey 1993). However, even after a diagnosis has been determined at this stage in crop development, it is too late to correct the deficiency.

If S is a limiting factor during crop growth and development, especially at the flowering stage, the result will be a loss in yield (Grant and Bailey 1993). The lack of S within the plant causes non-protein N to accumulate in the vegetative tissue and protein N levels to decline. The decrease in soluble protein content of the plant affects the rate of photosynthesis; therefore, plant growth slows and the yield potential declines due to the lack of carbohydrates available for plant growth (Ahmad et al. 1999).

2.2.5. Effect of Sulphur Fertilization on Canola Yield and Quality

Canola requires high amounts of fertilizer S to achieve maximum yields (Grant et al. 2003; Grant et al. 2004; Malhi and Gill 2002). Research has shown that rapeseed requires approximately 1.5 kg of S to produce 100 kg of seed (Grant and Bailey 1993). A typical canola crop grown in Manitoba, yielding 1960 kg ha^{-1} will remove approximately 22 kg S ha^{-1} (Manitoba Agriculture, Food and Rural Initiatives 2003) with 13 kg being stored in the seed (Manitoba Agriculture and Food 2001). Therefore, on well-drained, low S soils, it is recommended that 22 kg S ha^{-1} be applied as SO_4^{2-} to avoid S deficiency (Manitoba Agriculture, Food and Rural Initiatives 2003). Elemental S may be used as an S source; however, it must be broadcast in the year before it is required by the crop in order to be oxidized by soil microorganisms into SO_4^{2-} for crop uptake (Grant et al. 2003; Grant et al. 2004).

Canola plants respond to application of S fertilizer by increasing total plant S uptake (Warman and Sampson 1994) and storing more S in the seed (Grant et al. 2003; Malhi and Gill 2002). An increase in total S uptake has been observed with fertilization at all growth stages of oilseed rape, with maximum uptake occurring where 40 kg S ha^{-1} was applied along with a minimum of 150 kg N ha^{-1} (Donald et al. 1993). Higher S uptake results in a lower N:S ratio within the crop tissue (Donald et al. 1993; Warman and Sampson 1994). There is an interaction which occurs between N and S within the plant; therefore, to achieve the maximum benefit of S fertilization, adequate N must be available to the crop. The interdependence between N and S is covered in a later section.

On S-deficient soils, a decrease in chlorophyll content has been observed with application of sulphate-based fertilizers. However, where soil S levels were not limiting, S fertilization did not affect chlorophyll production (Grant et al. 2003). Lower chlorophyll content negatively affects canola yield, since less carbohydrate energy is available for seed development.

The application of S fertilizer has been shown to increase both the height of mustard plants, the number of branches on each plant, total dry matter of the crop (Saran and Giri 1990), as well as the number of pods and seeds per pod formed on each plant (Singh et al. 2002). Even though the increased uptake of S has influenced the growth of mustard, research on canola has shown that total dry matter accumulation does not increase with S fertilization (Warman and Sampson 1994). Warman and Sampson (1994) postulated that the available S contents of the soils used in their experiments were sufficient for dry matter production by canola, even though each soil tested low in extractable SO_4^{2-}.

Research on mustard in India has shown the application of S fertilizer to significantly increase overall seed yield (Saran and Giri 1990). The authors report that this may be due to an increase in both chlorophyll content and leaf area, which provides greater amounts of chlorophyll for seed production. Other mustard research in India has indicated that the application of 20 and 40 kg S ha^{-1} will potentially result in yield increases of 47% and 63%, respectively (Singh et al. 2002).

Rapeseed yields in Manitoba have been reported to increase by 300 to 670 kg seed ha^{-1} when S was applied at rates of 26 to 34 kg S ha^{-1}. Generally, 30 kg S ha^{-1} is sufficient to grow rapeseed on S deficient soils in Manitoba (Grant and Bailey 1993). Malhi and Gill (2002) found that application of S fertilizer without N significantly increased canola yields where the NO_3-N levels in the soil were between 15 and 38 mg N kg^{-1}. Where soil NO_3-N levels were below 13 mg N kg^{-1}, there was a tendency for yields to increase, but this was not statistically significant. The lack of S response where N levels are low is expected, due to the interaction between N and S in plant metabolism (see next section).

Similar to the application of N, additions of S fertilizer in high amounts can decrease the concentration of oil in rapeseed (Grant and Bailey 1993). However, this effect is quite variable. For example, S fertilization has also been shown to increase (Grant et al. 2003; Malhi and Gill 2002; Nuttall et al. 1987) and have no effect on oil content, even on S deficient soils (Grant and Bailey 1993). Protein content is increased by application of S on deficient soils (Grant and Bailey 1993), but this generally occurs only when adequate N is present. When S is applied alone, a change in protein content of the seed may not be observed (Malhi and Gill 2002). Many studies on rapeseed have shown the concentration of glucosinolates to increase with S fertilization (Fismes et al. 2000; Grant and Bailey 1993; Nuttall et al. 1987). Increased glucosinolate concentration may occur in some canola varieties; however, there is little concern about this effect as canola is now bred to have low glucosinolate content (Grant and Bailey 1993; Nuttall et al. 1987).

2.3. Nitrogen and Sulphur Interactions

Canola responses to N or S fertility individually are often not as great as for the two nutrients together. Each nutrient needs the other, in order to be utilized within the plant. As a result, without the required N needed for S synthesis, soil and/or fertilizer S is relatively useless to the canola plant and vice versa. The interdependence of these nutrients has been thoroughly studied, especially in canola production, since canola is very sensitive to S deficiencies.

2.3.1. Interdependence of Nitrogen and Sulphur in Plant Metabolism

Nitrogen and sulphur are both essential structural components of plant proteins (Ahmad et al. 2001; Rendig 1986). Therefore, since they are both required for protein synthesis (Aulakh et al. 1980; Donald et al. 1993; Grant and Bailey 1993; Janzen and Bettany 1984), an interaction between the two elements exists. As a result, plants grown under N-limiting conditions may exhibit an increase in protein concentrations as S supply is increased (Rendig 1986).

Sulphur is required for the conversion of NO_3^- to amino acids and protein within the plant (Ahmad and Abdin 2000). Generally, S deficiencies will cause an accumulation of amino acids and nitrates in the plant leaves, and degradation of protein in the chloroplasts (Fismes et al. 2000). Therefore, N fertilization on an S deficient soil may increase the accumulation of non-protein N forms within the plant, ie. NO_3^-, NH_4^+ or amides (Ahmad et al. 1999; Donald et al. 1993; Doyle and Cowell 1993; Grant and Bailey 1993).

In an environment where N is limiting, the addition of S fertilizer will cause an accumulation of non-protein S in the leaves and stems of the plant (Janzen and Bettany 1984). Canola grown under low-N, high-S conditions may also exhibit a higher concentration of glucosinolates in the seed (Blake-Kalff et al. 1998). However, S deficiencies may be less noticeable in plants grown in low N environments (Blake-Kalff et al. 1998) due to the redistribution of SO_4^{2-} from older leaves caused by N stress or by the reduced growth rate of the low-N plants. When N is added where S levels are insufficient, non-protein N may accumulate in the form of free amino acids (Grant and Bailey 1993). The low availability of either N or S will limit protein synthesis, leaving the alternate nutrient in its free form within the vegetative tissue.

When N and S are equally available to rapeseed, the activities of both ATP-sulphurylase and nitrate reductase are enhanced (Ahmad et al. 1999). These enzymes are responsible for nitrate and sulphate assimilation, respectively, and each enzyme is regulated by the other nutrient (Ahmad and Abdin 2000; Ahmad et al. 1999). Therefore, a deficiency of either N or S would cause a decline in the activity of the enzyme it regulates.

2.3.2. Effect of Nitrogen and Sulphur Fertilization on Canola

Variability in S fertility response reported in the earlier section may be due to the differences in N fertilization practices (Rendig 1986). The interdependence of N and S in plant metabolism creates a system where one nutrient cannot be used to its maximum potential without the other's presence. Therefore, it is important that both N and S be supplied to the crop through fertilization practices.

2.3.2.1. Interactive Effect of Nitrogen and Sulphur Fertilization on Canola. Janzen and Bettany (1984) found that increasing S fertilization results in an increase in S uptake by the rapeseed plant, regardless of N fertilization rate. Warman and Sampson (1994) observed a similar response in S fertilized canola. When the S rate was low, an increase in N fertilization reduced the S uptake of the crop, due to the suppression of seed yield. When high S rates were maintained, the application of N fertilizer increased the dry matter content of the rapeseed plants, thereby increasing the overall uptake of S. A similar trend was observed for N uptake, where increases in N fertilization lead to higher N uptake, especially at the highest rate of S. Fismes et al. (2000) reported that, on average, N uptake increased with increasing rates of S. This is also due to the overall increase in dry matter production observed under conditions of high N and S supply.

The concentration of S within the rapeseed plant generally increases in response to an increase in S rate and decreases in response to increasing N rate (McGrath and Zhao 1996), whereas the concentration of N in the seed decreases as both N and S rates increase (Janzen and Bettany 1984). The concentration of N and S in the stems and pods is particularly low where high seed yields are observed. The low N and S concentration in the stems and pods may occur because the nutrient reserves are depleted to meet the needs for seed production. In this case, N and S concentration of the leaves may be greater, because senescence occurs before the nutrients in the leaves can be depleted.

The N:S ratio within the plant tissue is often an indication of whether the proper balance between N and S uptake exists for maximum yield potential (Donald et al. 1993). Where high N and low S rates were applied, the resulting high N:S ratio in the leaves and stem was due to the non-protein N levels. The increase in free N within the plant tissue when the N:S ratio is high can be detrimental to canola yields (Doyle and Cowell 1993). When N is applied on soils that are very low in S, the resulting rapeseed yields are reduced (Doyle and Cowell 1993; Janzen and Bettany 1984) primarily due to empty pods (Doyle and Cowell 1993).

Canola is a relatively N-inefficient plant, as it is not capable of withdrawing all of the N from its leaves before senescence (Fismes et al. 2000). As well, canola is considered to be S-inefficient (McGrath and Zhao 1996), because a high proportion of S can be found in the non-protein form, even under S-deficient conditions. When rapeseed is grown on soil with a balanced supply of both N and S, the efficiency of canola to utilize each nutrient is increased (Fismes et al. 2000). For example, the use of both N and S fertilizer on canola increases the activity of nitrate reductase. The result is a lower N concentration in the leaves (Ahmad et al. 2001); therefore, the plant loses less N via senescence. As a result of balanced N and S fertilization, the N use efficiency of the crop increases (Ahmad et al. 2001).

The application of S when N levels are low will most likely result in no seed yield response (Grant and Bailey 1993; Janzen and Bettany 1984). A combination of N and S may produce large increases in rapeseed yield (Von Uexkull 1986), much larger than those seen when either of the two nutrients is applied alone (Aulakh et al. 1980). The protein N-level of the rapeseed increased in response to the N fertilization treatment; however, protein S-levels increased as a result of both N and S fertilization (Zhao et al. 1997). With the required level of N and S, ATP-sulphurylase and nitrate reductase activities are increased leading to a greater production of N- and S-containing proteins in the seed (Grant and Bailey 1993).

2.3.2.2. "Sulphur Dilution Effect" with Nitrogen Fertilization. Due to the interdependence of N and S in canola growth, the application of N often increases the uptake of S. Nitrogen application stimulates vegetative growth and causes the overall biomass of canola to increase significantly (Janzen and Bettany 1984). The increased growth creates a higher demand for S (Blake-Kalff et al. 1998); however, the concentration of S in the plant decreases as N rate is increased (Blake-Kalff et al. 1998; Donald et al. 1993; McGrath and Zhao 1996) because the proportional increase in accumulation of dry matter exceeds that for the S (Janzen and Bettany 1984). This occurrence is referred to as the "sulphur dilution effect". In some components of the plant, N may also be "diluted" as the increase in dry matter production is greater than the increase in N accumulated by the plant.

The dilution of S in the plant may have significant agronomic consequences in canola production. The lowered concentration of S in the plant may not be sufficient to meet the plant's S requirements for photosynthesis and seed production. With high N application, the plant's ability to absorb and assimilate S may also be compromised (Janzen and Bettany 1984).

2.3.2.3. Nitrogen and Sulphur Balance in Canola Production. Fismes et al. (2000) emphasized the practise of applying a combination of N and S fertilizers on oilseed rape when grown on S-deficient soils. Maintaining a balance between N and S within the plant should aid in the development of reproductive organs and decrease the occurrence of pod abortion, leading to higher yields. Singh and Nad (2000) found that simply increasing N fertilization rates in mustard production, while maintaining a stable level of S fertilization, did not increase seed yield. Instead, S rates must be increased proportionally to keep up with the plants demand for protein synthesis.

An N:S ratio of 7.5:1 or less in the mustard grain has been reported to be the ideal level for seed production (Aulakh et al. 1980). However, in rapeseed production, Zhao et al. (1997) found that the N:S ratio could be as high as 10:1, above which significant yield losses occurred. To ensure that the N:S ratio of oilseed rape tissue remains below 10:1, S fertilization practices may be utilized (McGrath and Zhao 1996).

When attempting to maintain a tissue N:S ratio of 10:1, it is important to understand the nutrient content in the soil to obtain maximum yields. The desired N:S ratio in the soil for canola is 7:1 on prairie soils and can be calculated as [(soil nitrate-N + fertilizer N)/(soil sulphate-S + fertilizer S)] (Janzen and Bettany 1984). However, due to the uneven spatial and temporal distribution of plant available S in the soil, it may be difficult to ensure high yields based on the use of an N:S ratio from soil tests (Bailey 1987).

Even though S availability may not be accurately predicted, an N:S ratio has been a widely accepted tool for fertility management of canola on the Canadian Prairies. Manitoba Agriculture, Food and Rural Initiatives (2003) recommends that canola be fertilized using an N:S ratio of between 5:1 and 8:1 for applied fertilizer. Similarly, Saskatchewan Agriculture, Food and Rural Revitalization (2001) recommends an N:S ratio of 5:1 to 7:1 for optimal yield. Providing adequate fertilizer S, even on soils that have sufficient soil test S guarantees that a producer will maximize canola yields.

2.4. Influence of Cultivar on the Agronomic Characteristics of Canola

In agronomic production, it is important to have variability within a cropping species to maintain its genetic diversity. Genetic diversity increases the range of traits from which breeders can select to increase the agronomic and economic viability of a new variety (Burton et al. 2004). Each variety is then bred to exhibit traits that may be slightly different than other varieties on the market. In a study on canola quality germplasm from three different breeding programs, Agriculture and Agri-Food Canada, Saskatchewan Wheat Pool and Agriculture Victoria, Burton et al. (2004) found that the genetic similarity coefficient within these programs ranged from 0.60 to 0.98. Therefore, each cultivar may have different characteristics that can influence its agronomic potential.

Sana et al. (2003) carried out a study on the production differences between seven different canola cultivars and found that both yield and oil production differed significantly between the cultivars. As well, differences were seen in the number of pods per plant and number of seeds per pod, which correspond to the higher yields. Genetic variability may also dictate the time required for a plant to mature. In general, hybrid cultivars mature later than open-pollinated cultivars; however, some hybrid varieties are earlier-maturing (Starmer et al. 1998).

A good example of breeding for the purpose of increased yields is that of hybrid canola. On average, hybrid canola produces seed and biomass yields greater than open-pollinated varieties. However, there is still genetic and agronomic variability among cultivars within the hybrid or open-pollinated groups. Variability is important in maintaining genetic diversity, but it creates difficulties when making generalizations about these two groups of canola cultivars. While hybrid cultivars are generally high yielding, there may be some varieties that produce poor yields when compared to a higher yielding variety of open-pollinated canola.

2.5. Hybrid Canola Cultivars

Hybrid canola cultivars now occupy a large percentage of total canola acreage. The increased use of hybrid canola cultivars has been mainly due to the higher yield potential of these varieties. In 2000, 15 percent of canola grown in Canada was of a hybrid variety, compared to 35 percent grown in 2003 (Pioneer Hi-Bred Limited 2004).

2.5.1. Yield Potential of Hybrid Canola Cultivars

Many new hybrid canola varieties have been developed in an effort to achieve higher grain yields. Research has shown that hybrid canola cultivars have the potential to yield 12% higher than open pollinated varieties under an identical fertility regime (Brandt et al. 2002; Karamanos et al. 2002). Van Deynze et al. (1992) reported that hybrid canola had the potential to yield 24% higher than open-pollinated cultivars, when growing conditions were weed-free. As a result, producers may be able to decrease the seeding rate of hybrid canola by 25%, compared to open-pollinated cultivars, without reducing yield (McVetty et al. 1987). The ability to decrease seeding rates is of economic importance to hybrid canola growers, as the hybrid seed is often twice as expensive as open-pollinated seed (Lamb and Johnson 2004).

As well as increased seed yield, hybrid canola typically exhibits a more vigorous growth habit, leading to higher biomass accumulation compared to open-pollinated varieties (Brandt et al. 2002; Harker et al. 2003; Zand and Beckie 2002). In an experiment by Brandt et al. (2002), Invigor (a hybrid) and Quantum (an open-pollinated) canola cultivars were seeded to three levels of N fertility based on 67%, 100% and 133% of a target fertility level. The reported mean harvest biomass of Invigor canola was, on average, 12% higher than that of the open pollinated variety Quantum. This trend was seen in seven of the eight site years in which the experiment took place.

2.5.2. Effect of Fertilization on Hybrid and Open-pollinated Canola Cultivars

2.5.2.1. Effect of Nitrogen Fertilization on Yield and Biomass. Karamanos and Flore (2002) investigated the yield response to N for four different parent-daughter pairs of canola. Four hybrid canola cultivars, or daughters, and their respective parent varieties were grown with increasing rates of N fertilizer. In all cases, the hybrid varieties yielded higher than the open-pollinated parent varieties. In two of the four cases, the hybrid exhibited maximum yield at an N rate higher than that of its parent. The utilization of fertilizer N was lower for the hybrids than for the open-pollinated cultivars, indicating that the hybrids used soil N resources more efficiently.

Brandt et al. (2002) studied the effect of six N rates (0, 30, 60, 90, 120 and 150 kg actual N ha^{-1}) on various agronomic factors of the two canola cultivars. Maximum harvest index occurred around 94 kg N ha^{-1} for the hybrid cultivar and 129 kg N ha^{-1} for the open pollinated variety. The vigorous growth habit observed early in the growing season by the hybrid cultivar may have depleted soil water, leaving less available during filling. The authors postulated that this may have caused the difference in the harvest indices of the two cultivars. However, the harvest index of the hybrid cultivar was still consistently higher than that of the open pollinated, indicating a greater production of grain per unit biomass by the hybrid variety.

2.5.2.2. Effect of Nitrogen fertilization on Sulphur Concentration. The addition of N fertilizer on hybrid canola may cause a decrease in the total plant concentration of S (Deibert et al. 2002). Since hybrid canola typically exhibits higher dry matter yields than open-pollinated canola (Brandt et al. 2002; Deibert et al. 2002), N fertilization may stimulate further dry matter growth and therefore accentuate the "sulphur dilution effect". The exaggerated growth of hybrid canola leaves the plant struggling to keep up with its S uptake. In contrast, open-pollinated varieties may exhibit an increase in plant S concentration when fertilized with N. The lesser dry matter growth response to N fertilization in open-pollinated varieties may lead to a less severe reduction in S concentration within open-pollinated canola, compared to hybrid canola.

Even though hybrid varieties may have a lower plant S concentration with N fertilization, the N:S ratio within the hybrid canola seed may be lower than that of an open-pollinated cultivar grown under similar conditions (Deibert et al. 2002). For example, two hybrid varieties, Hyola401 and Hyola357, had lower seed N:S ratios than three open-pollinated varieties, Hudson, Pheonix and 45A71. The decrease in the ratio, combined with higher seed yields, indicates the ability for the hybrids to utilize more S from the soil and/or fertilizer.

2.5.2.3. Effect of N:S Fertilization Ratio on Yield. Hybrid canola varieties have been described as being more efficient "scavengers" of soil nutrients (Karamanos and Flore 2002; Karamanos et al. 2002) due to their ability to utilize soil N more efficiently than open-pollinated varieties. This may have implications for the fertilization practices that are carried out on hybrid canola varieties. The ability of hybrids to extract N and S from the soil will determine the need for fertilizer sources.

Karamanos et al. (2002) found that open-pollinated canola cultivars exhibit a response to fertilization practices that are based on an N:S ratio. Both hybrid and open-pollinated varieties were exposed to three N:S ratios, 12:1, 6:1 and 1.2:1, over six N rates ranging from 0 to 200 kg N ha^{-1}. The open-pollinated cultivars showed increased seed yields as the N:S ratio decreased. In contrast, the hybrid cultivars did not show any significant differences in seed yield over the three N:S ratios. As mentioned in the previous section, Deibert et al. (2002) found that the N:S ratio of the hybrid canola seed was lower than that of the open-pollinated varieties, indicating that hybrids may be better at utilizing soil and/or fertilizer S.

The higher above-ground biomass exhibited by hybrid cultivars (Brandt et al. 2002; Harker et al. 2003; Zand and Beckie 2002) may also be an indicator of the hybrid canola cultivar's ability to "scavenge" for S in the soil. Higher biomass production may cause an increase in the rate of evapotranspiration (ET) by the plant. This could mean that hybrid canola takes up more water from the soil, thereby accessing more water-soluble nutrients, such as NO_3^- and SO_4^{2-}, from the soil. It is possible that an increase in above-ground biomass production may be countered by an increase in below-ground biomass production, leading to a deeper and denser rooting habit. Deeper growing roots would increase the exposure of the hybrid canola to sub-soil SO_4^{2-}, lessening the need for S fertilization.

Currently, fertilizer rates are based on an N:S ratio that will match the canola's requirements for both nutrients. N and S uptake by the crop generally follows a ratio of

7:1 (Janzen and Bettany 1984); therefore, fertility recommendations are based on this information. New research into the fertility requirements of hybrid and open-pollinated canola varieties has focused on the seed yield of the crop, rather than total uptake of nutrients. Seed yield has shown that, for hybrid cultivars, there is no response to S fertilization on soils with adequate soil test S, whereas open-pollinated varieties still exhibit a need for S fertilizer to optimize yield (Karamanos et al. 2002).

2.6. Rooting Habit of Canola

Subsoil NO_3^- and SO_4^{2-} reserves are important sources of N and S for canola crops grown in the Canadian Prairies. Therefore, the rooting habit of canola and specific cultivars of canola play a significant role in determining the amount of N and S that is accessible for plant uptake.

Canola has a deep reaching, tap root system and studies in North Dakota have reported a maximum average root depth of 113 cm (Merrill et al. 2002); however, in Prairie Canadian soils, it may also be capable of extracting water to a depth of 165 cm (Angadi et al. 1999; Johnston et al. 2002).

2.6.1. Effect of Cultivar on Rooting Habit

Very little research has been carried out on the effect of canola cultivar on rooting habit. Kamh et al. (2005) studied the difference in root production between the cultivars, Apex, an N-efficient variety, and Capitol, and N-inefficient variety. At bolting, these researchers reported no difference between the number of roots produced by either cultivar; however, at flowering, the N-efficient cultivar produced a greater number of roots than the N-inefficient cultivar, although this occurred only where no N fertilizer was applied.

2.6.2. Effect of Nitrogen Fertilization on Root Depth

N fertilization may decrease the total root length of canola (Vos et al. 1998; Kamh et al. 2005); however research on this topic has produced variable results. Kamh et al. (2005) found that, at the flowering stage, unfertilized canola exhibited greater root production and soil N depletion than canola fertilized with 227 kg N ha^{-1}. In contrast, Kappen et al. (2000) reported that the production of rapeseed roots increased with the application of N fertilizer.

2.7. Research Needs

As the overall acreage of higher yielding canola cultivars, such as hybrids, is increasing, it is important to understand any agronomic requirements of these cultivars that differ from the traditional varieties. In general, the higher yielding hybrids display increased above-ground biomass with higher production of pods per plant than lower yielding varieties. The higher N and S utilization by hybrids has led to the postulation that these varieties may be more efficient "scavengers" of soil N and S. As a result, hybrid canola cultivars may have decreased sensitivity to fertilizer S additions. As well, if hybrid canola cultivars are accessing greater amounts of N and S from the soil, then the total N and S accumulated by hybrid cultivars may exceed that accumulated by open-pollinated cultivars. Therefore, research is needed to better understand the mechanisms by which higher yielding cultivars are accessing these nutrients.

The greater above-ground biomass accumulation by hybrid canola cultivars may be an indication that these cultivars have the capacity to accumulate more N and S than open-pollinated cultivars. It is also possible that greater above-ground growth in hybrid canola may also correspond to an increase in root growth and distribution, allowing hybrid canola greater access to subsoil S, thus lessening the need for fertilizer S. As well, since NO_3^- and SO_4^{2-} are both water-soluble nutrients, if hybrid canola cultivars extract more soil water than open-pollinated canola cultivars, then a greater quantity of these nutrients may move towards the canola roots via mass flow. These issues need to be explored to gain greater knowledge about hybrid canola cultivars and their specific agronomic requirements.

3. OBJECTIVES

The main purpose of this study was to assess the mechanism by which hybrid canola cultivars better utilize soil and/or fertilizer N and S. Research by Western Cooperative Fertilizers Limited (Westco) has demonstrated that hybrid canola cultivars are better "scavengers" of soil nutrients than open-pollinated varieties, especially with regards to S. Therefore, hybrid cultivars required less fertilizer S to obtain maximum seed yields.

This study consisted of two separate experiments; a canola crop experiment, where two canola cultivars were subjected to different rates of N and S, and a follow crop experiment, where wheat was seeded to the canola stubble without N or S fertilizer. The specific objectives of these two experiments were:

1. to determine the effect of canola cultivar and fertilizer treatment on the accumulation of N and S by the canola crop;
2. to determine if there are any differences in the rooting habit or activity of the hybrid and open-pollinated canola cultivars that may be leading to the increase in N- and S-efficiency by the hybrid canola; and
3. to determine the effect of soil-N and -S removal by the hybrid and open-pollinated canola cultivars on the yield and nutrient recovery by a following wheat crop.

4. MATERIALS AND METHODS

4.1. Site Selection and Description

The experiment was part of a larger study initiated by Westco on the effect of N:S ratio on hybrid and open-pollinated canola cultivars at various locations across the Canadian Prairies. The intensive study described in this chapter was carried out over two growing seasons, 2003 and 2004, at the Proven Seed Research Farm near Rosebank, Manitoba on a Gleyed Rego Black sandy loam soil of the Reinland soil series. The background NO_3^- concentrations at this site were medium for canola production, according to Manitoba Agriculture and Food (2001), whereas the SO_4^{2-} concentrations were considered very high.

4.2. Canola Crop Experiment 2003

4.2.1. Experimental Design and Treatments

In 2003, a split plot design was used, where canola cultivar was the main plot and fertilizer treatment was the subplot. The two canola cultivars used in this experiment were 45H21 (a hybrid cultivar) and Conquest (an open-pollinated cultivar); both of the chosen varieties were tolerant to Roundup herbicide. Fertilizer treatments consisted of an unfertilized control treatment and two fertilized treatments: an N without S treatment and an N with S treatment. In both fertilized treatments, the N was applied at a rate of 160 kg N ha^{-1}. In the N with S treatment, the S was applied at a rate of 27 kg S ha^{-1}; therefore, the N:S ratio for this treatment was 6:1. Each treatment was replicated four times, resulting in a total of 24 subplots within the experimental area. The selected cultivar and fertilizer treatments were selected from a variety N and S rates from a larger N:S ratio project being conducted by Westco. The treatments were duplicated and placed beside the original treatment from the N:S ratio project. The N fertilizer rate for the experiment was selected according to past research on N:S ratio in canola production by Westco. It is at this level of N fertilization that hybrid canola cultivars exhibit the greatest yield advantage over open-pollinated varieties; therefore, we chose this N rate as the best for testing our hypothesis.

4.2.2. Crop Measurements

Six rows of canola were seeded to each plot on May 13th, 2003 with a 1.8 m wide airseeder on 22.9 cm row spacing. Triple super phosphate (0-45-0) was applied in the seedrow at a rate of 25 kg P_2O_5 ha^{-1}. Variable rates of N and S were side-banded as urea (46-0-0) and ammonium sulphate (20.5-0-0-24), along with 30 kg K_2O ha^{-1}. Glyphosate, as Roundup Transorb, was applied at the recommended rate (based on the Manitoba Crop Protection Guide) using a 4 m wide ATV-mounted plot sprayer. Additional canola was seeded in the border plots to minimize the edge effect on the outer plots.

At midseason (70% bloom), above ground plant tissue was hand harvested from each of the 24 subplots, removing an area of two-rows by one-metre. The samples were dried at 35 to 40°C, until a constant weight was reached. From this weight, total dry matter biomass (kg ha^{-1}) was calculated. The entire sample was then ground using a Wiley mill to pass through a 2 mm sieve and a subsample was assayed for N and S by combustion and nitric acid digest, respectively (Jones 2001).

At physiological maturity, four-rows by one-metre were hand harvested from each subplot. Each sample was dried, threshed and the yield of the grain and straw were determined and adjusted to 0% moisture content. The straw and grain were ground and analyzed for N and S following the same procedure described for the midseason tissue samples. Total N and S accumulated by the above ground canola tissue were calculated on a dry matter weight basis for both midseason (eg. % N content x midseason biomass/100) and harvest (eg. [(% grain N x grain yield) + (% straw N x straw yield)]/100) samples.

Below ground biomass and rooting depth was determined using the root core break method (Bohm 1979). At the 70% bloom stage, a single intact soil core (5 cm in diameter and 120 cm in length) was removed from each subplot. Each core was frozen at -22°C until it could be analyzed, at which time the cores were thawed and divided into 10 cm increments. Each segment was broken in half along the long axis and the roots protruding from each breakage face were counted. After the root count was recorded (no. root axes m^{-2}), the soil core segment was washed in a Gillison's Hydropneumatic Root Washer (Gillisons's Variety Fabrication Inc., Benzonia, MI) and the clean root mass was dried at 65°C for 24 hours, weighed and recorded as root biomass (g m^{-2}).

4.2.3. Soil Sampling and Analyses

To characterize the background concentrations of NO_3^- and SO_4^{2-} to depth at the experimental site, soil samples were collected in June 2004 to a depth of 2.4 m using a Giddings tractor-mounted soil auger (Giddings Machine Company, Windsor, CO) (Table 4.1). Moist soil samples were collected from the 160 kg N ha^{-1}: 27 kg S ha^{-1} treatment for each cultivar in 30 cm depth increments and combined over all four replications. Soil samples were assayed for water-soluble NO_3^- and SO_4^{2-} using a 0.1 M KCl solution (Jones 2001).

Table 4.1. Background NO_3^- and SO_4^{2-} concentrations (kg ha^{-1}) under each cultivar in 2004 at Rosebank.

	Soil NO_3^-		Soil SO_4^{2-}	
Depth (cm)	45H21 (HY‡)	Conquest (OP§)	45H21 (HY)	Conquest (OP)
0-30	20	20	269+	85
30-60	31	29	94	85
60-90	56	45	242	152
90-120	45	36	269+	269+
120-150	58	34	269+	269+
150-180	31	27	269+	269+
180-210	27	18	269+	269+
210-240	29	16	269+	269+

‡ HY = Hybrid canola cultivar.
§ OP = Open-pollinated cultivar.

Soil samples taken throughout the growing season were split into depths of 0 to 10 cm, 10 to 30 cm, 30 to 50 cm, 50 to 70 cm, 70 to 90 and 90 to 110 cm depth increments. The 0 to 10 cm soil sample was analysed for macro- and micronutrients at the preseeding sampling time. Subsequent soil samples, carried out at the 70% bloom stage and post-harvest were analysed for NO_3^- and SO_4^{2-} only.

4.2.4. Soil Moisture Measurements

Soil moisture content was determined using a Troxler 4302 Neutron Moisture Meter (Troxler Electronic Laboratories Inc., Research Triangle Park, NC). One aluminum access tube was inserted into each of the 24 subplots within 6 days of seeding. The count recorded by the meter was converted into a volumetric soil moisture content based on a generalized calibration curve, $y = 0.0702x + 0.2401$. The initial soil moisture reading was taken at crop emergence and used as a baseline to compare water loss under each treatment throughout the growing season. Soil moisture content was determined for the 10 to 30 cm, 30 to 50 cm, 50 to 70 cm, 70 to 90 cm and 90 to 110 cm soil depths. Soil moisture was not determined for the 0 to 10 cm soil depth, as the neutron moisture meter cannot accurately depict the moisture content at this depth. Additional moisture readings were taken every three weeks after emergence, until the final measurement just prior to harvest. Total net water loss for the growing season was determined by subtracting the moisture content in the soil at harvest from the moisture content at emergence. Total net water loss for the 10 to 110 cm soil depth was added to the total growing season rainfall to calculate evapotranspiration (ET).

4.3. Canola Crop Experiment 2004

A similar experimental site was set up near Thornhill, Manitoba in 2004; however, due to wet and cool weather conditions, this site year is not included in the results and discussion. The weather in 2004 complicated the analysis of the Thornhill site as it lengthened the flowering-time of the canola and the canola was not able to reach maturity before harvest. As well, a perched water table at approximately 70 cm below the ground affected the soil moisture data and rendered it ineffective for measuring water use efficiency and root activity. The dense layer of shale gravel at the 60 to 70 cm soil depth also created difficulties when extracting soil cores to monitor root depth.

4.4. Wheat Crop Experiments 2004

4.4.1. Experimental Design

In 2004, a wheat crop experiment was set up at the Proven Seed Farm near Rosebank, Manitoba. AC Barrie wheat was seeded on May 13, 2005 on to each of the plots from the 2003 canola experiment. At planting, 30 kg ha^{-1} of both P_2O_5 and K_2O were placed with the seed of the wheat crop. The wheat was left unfertilized with N and S, to rely on the residual N and S remaining in the soil subsequent to the growth of the canola cultivars. Therefore, the data generated from the wheat was used to determine the residual effect of the canola cultivar and fertility treatments on N and S availability.

4.4.2. Crop Measurements

At mature harvest, two-rows by one-metre were removed from each of the 24 subplots. The collected wheat crop was threshed and the seed and straw were weighed to determine yield, which was adjusted to 0% moisture content. Both the grain and straw were ground and assayed for N and S, using the same procedure as for the canola in 2003. Total plant N and S accumulated by the wheat was determined on a dry matter basis using the tissue analyses from the lab (eg. [(% grain N x grain yield) + (% straw N x straw yield)]/100).

4.4.3. Soil Sampling and Analyses

After harvest of the wheat, soil samples were taken from each subplot at depths of 0 to 15 cm, 15 to 30 cm and 30 to 60 cm. Each sample was analyzed for NO_3^- and SO_4^{2-} using the same method as for the canola crop experiment in 2003. Total NO_3^- and SO_4^{2-} contents over the 0 to 60 cm soil depth were calculated and combined with the total plant accumulation of N and S to report the recoverable N and S in the crop year following the two canola cultivars.

4.5. Data Analyses

Statistical analyses were carried out using the Mixed Procedure of the Statistical Analysis System (SAS) v. 8.2 package (SAS 2001). The Proc Univariate function of SAS was used to test the data for normality. Most of the soil and crop variables showed normal distributions of either the raw data and/or the residuals of the data; therefore, transformations were not needed. In the few cases where the raw data and residuals of the data were non-normally distributed, transformation of the data did not give results different than those for the initial non-transformed data. Consequently, all statistical analyses were performed and reported on the initial, untransformed data.

The ANOVA model used to test the main plot (cultivar) and subplot (fertilization) effects included: cultivar treatment, fertilization treatment and cultivar treatment by fertilization treatment. Where soil depth and/or time were factors, a separate ANOVA was run on each soil depth and/or each time, to limit the complexity of the model. A larger ANOVA model that included the added subplots was carried out to determine the effects of soil depth and time, but these were not reported. The LSMEANS of SAS was used to compare the two cultivars, fertilization treatments and fertilization treatments applied to each cultivar. For all soil and crop variables, a probability level (α) of 0.10 was used as the threshold for significance.

5. RESULTS AND DISCUSSION

5.1. Weather Conditions

Weather conditions for 2003 were within range of the 30-year climatic averages for Morden, MB, the nearest Environment Canada weather station. In 2004, the weather was abnormally cool and wet; total growing season precipitation was approximately 110 mm greater than normal.

Table 5.1. 2003 and 2004 meteorological data for Morden, MB‡.

	Year		
	2003	2004	30-Year Average
May			
Precipitation (mm)	75.8	166.2	61.6
Average Air Temperature (°C)	12.9	8.5	12.9
June			
Precipitation (mm)	96.6	47.4	84.4
Average Air Temperature (°C)	17.3	15.2	17.7
July			
Precipitation (mm)	22.6	59.8	71.2
Average Air Temperature (°C)	20.3	19.0	20.1
August			
Precipitation (mm)	41.4	74.6	69.9
Average Air Temperature (°C)	21.5	14.9	19.1

‡ Source: Environment Canada.

5.2. Canola Crop Experiment 2003

5.2.1. Midseason Harvest

Biomass accumulation at 70% bloom was significantly higher for the hybrid cultivar than for the open-pollinated cultivar (Table 5.2). On average, hybrid canola cultivars exhibit greater above-ground biomass than open-pollinated varieties (Brandt et al. 2002; Harker et al. 2003; Zand and Beckie 2002); therefore, the larger biomass of the hybrid in this experiment was expected. However, it is important to note that for all parameters described in this chapter, the response of the hybrid cultivar may not accurately portray how all hybrid varieties would respond to these select treatments. There is a great deal of variability between the characteristics of growth and development exhibited by each cultivar within the hybrid and open-pollinated groups.

When averaged over both cultivars, the canola biomass accumulation at the 70% bloom stage increased with the addition of fertilizer. The 160 kg N ha^{-1}: 27 kg S ha^{-1} fertilizer treatment had the greatest biomass yield, greater than both the 160 kg N ha^{-1}: 0 kg S ha^{-1} and control treatments (Table 5.2). The response to S fertilization may be indicative of S-deficient soil at the site; however, the SO_4^{2-} concentration in the soil was high at this site (Table 4.1). Warman and Sampson (1994) found that S fertilization did not increase dry matter accumulation when soil test S concentrations were adequate for canola production. Therefore, the reason for the increase in dry matter accumulation where fertilizer S was added at this site is not known.

The S concentration of the canola tissue decreased with the addition of fertilizer N. The decrease in S concentration with N fertilization is an example of the "sulphur dilution effect". Under these circumstances, the plant cannot increase its uptake of S from the soil sufficiently to keep up with the increase in biomass accumulation due to N fertilization (Blake-Kalff et al. 1998). The tissue S concentrations for all treatments were high relative to the critical S concentration (0.25%) for canola at flowering (Grant and Bailey 1993). The total N and S accumulated by the canola crop at flowering (Table 5.2) was

Table 5.2. Midseason biomass, N and S concentrations and N and S accumulations of canola at the Rosebank-03 site.

Treatment: Cultivar	Treatment: Fertilizer	df	Biomass	N Concentration	S Concentration	N Accumulation	S Accumulation
			--kg ha^{-1}--	--------%--------		--------kg ha^{-1}--------	
45H21 (HY[‡])	Control		5878	2.6	0.72	152.1	42.6
	160 kg N ha^{-1}: 0 kg S ha^{-1}		6929	2.5	0.55	168.6	39.2
	160 kg N ha^{-1}: 27 kg S ha^{-1}		8273	2.6	0.56	209.9	46.4
Conquest (OP[§])	Control		3758	3.5	0.94	127.5	33.9
	160 kg N ha^{-1}: 0 kg S ha^{-1}		4295	3.4	0.87	152.9	36.6
	160 kg N ha^{-1}: 27 kg S ha^{-1}		6761	3.7	0.79	254.5	54.5
Cultivar means							
45H21 (HY)			7027a	2.5b	0.61b	176.9	42.8
Conquest (OP)			4938b	3.5a	0.87a	178.3	41.6
	Fertilizer means						
	Control		4818b	3.0	0.83a	139.8b	38.3
	160 kg N ha^{-1}: 0 kg S ha^{-1}		5612b	2.9	0.71ab	160.7ab	37.9
	160 kg N ha^{-1}: 27 kg S ha^{-1}		7517a	3.1	0.68b	232.2a	50.4
ANOVA		df	$P > F$				
Cultivar		1	0.0008*	0.0049*	0.0002*	0.9513	0.8254
Fertilizer		2	0.0210*	0.8469	0.0846†	0.0597†	0.1447
Cultivar x Fertilizer		2	0.5738	0.8961	0.7684	0.4289	0.4085
C.V. (%)			18.8	23.8	19.8	35.7	30.1

‡ HY = Hybrid canola cultivar.

§ OP = Open-pollinated cultivar.

a-b Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

very high due to the yield potential of these cultivars. Similar to S tissue concentration, the greater N accumulation with the addition of S fertilizer was again not expected due to the high soil-S concentrations in the soil at the Rosebank experimental site. Therefore, as adequate tissue concentrations of S were found for all treatments, the canola's response to S fertilization is even more perplexing.

The hybrid canola cultivar had a plant tissue concentration of N and S that was lower than that of the open-pollinated cultivar (Table 5.2). The higher biomass of the hybrid cultivar offset the lower N and S tissue concentrations, resulting in a similar accumulation of N and S overall. Therefore, although the biomass accumulation by the hybrid cultivar was greater than the open-pollinated, there was no statistical difference between the total accumulation of N and S by each cultivar. Furthermore, there was no interaction between the effects of cultivar and fertilizer treatment on N or S concentration or accumulation, indicating that the uptake of fertilizer N and S by the two cultivars followed a similar pattern.

5.2.2. Mature Harvest

Many of the differences seen between cultivars and fertilizer treatments at the midseason sampling period were no longer significant at mature harvest. The whole-plant biomass remained greater for the hybrid cultivar than for the open-pollinated cultivar (Table 5.3). There were no significant differences in the biomass accumulated under any of the three fertilizer treatments; however, there seems to be a trend of increased biomass accumulation with the addition of N and S fertilizer.

Table 5.3. Mature harvest biomass, N and S concentration and N and S accumulations of whole-plant canola at the Rosebank-03 site.

Treatment						
Cultivar	Fertilizer	Biomass	N Concentration	S Concentration	N Accumulation	S Accumulation
		---kg ha^{-1}---	---%---		---kg ha^{-1}---	
45H21 (HY[‡])	Control	7376	1.5	0.60	108.0	44.8
	160 kg N ha^{-1}: 0 kg S ha^{-1}	11041	1.7	0.51	188.0	57.3
	160 kg N ha^{-1}: 27 kg S ha^{-1}	11918	1.8	0.50	217.1	59.0
Conquest (OP[§])	Control	6626	1.7	0.66	113.4	43.8
	160 kg N ha^{-1}: 0 kg S ha^{-1}	6739	1.8	0.68	124.4	45.3
	160 kg N ha^{-1}: 27 kg S ha^{-1}	7830	2.0	0.74	156.2	56.6
Cultivar means						
45H21 (HY)		10112a	1.7	0.54b	171.0	53.7
Conquest (OP)		7065b	1.8	0.69a	131.3	48.6
	Fertilizer means					
	Control	7001	1.6	0.63	110.7b	44.3b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	8890	1.8	0.59	156.2ab	51.3ab
	160 kg N ha^{-1}: 27 kg S ha^{-1}	9874	1.9	0.62	186.6a	57.8a
ANOVA	df			$P > F$		
Cultivar	1	0.0138*	0.1623	0.0524†	0.1132	0.6396
Fertilizer	2	0.3051	0.1034	0.8101	0.0536†	0.0593†
Cultivar x Fertilizer	2	0.4250	0.7686	0.1878	0.1421	0.5105
C.V. (%)		23.0	10.9	14.0	21.7	23.4

[‡] HY = Hybrid canola cultivar.

[§] OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

Mature harvest seed yield was greater for the hybrid cultivar than for the open-pollinated cultivar (Table 5.4); this agrees with the findings of Brandt et al. (2002) and Karamanos et al. (2002). Seed yield was also significantly higher for the fertilized treatments compared to the control treatment. The addition of N and S fertilizer resulted in numerically higher seed yields than for N only; however, these two fertilized treatments were not statistically different. The interaction between cultivar and fertilizer treatment was nearly significant for seed yield, indicating that the hybrid cultivar may have responded to N and S fertilization in this situation, while the open-pollinated cultivar did not.

Along with higher seed yields for the hybrid cultivar, hybrid straw yields were also significantly greater than those of the open-pollinated cultivar. As well, straw yields responded to the fertilizer treatment, with the 160 kg N ha^{-1}: 27 kg S ha^{-1} treatment yielding higher than the control. The 160 kg N ha^{-1}: 0 kg S ha^{-1} treatment was similar to both the control and the 160 kg N ha^{-1}: 27 kg S ha^{-1} treatment.

The S concentration remained lower for the hybrid cultivar than for the open-pollinated cultivar (Table 5.3). Therefore, similar to the midseason data, there was no difference in total plant accumulation of S between the two cultivars. The tissue concentration of N in the open-pollinated cultivar was no longer higher than in the hybrid cultivar and the total accumulation of N for the cultivars were still not significantly different.

Table 5.4. Canola seed yield, straw yield, evapotranspiration, grain and straw water use efficiencies (WUE) at the Rosebank-03 site.

Treatment						
Cultivar	Fertilizer	Evapotranspiration	Seed Yield	Straw Yield	WUEseed	WUEstraw
		----------mm---------	--------kg ha^{-1}--------		------kg ha^{-1} mm^{-1}------	
45H21 (HY‡)	Control	305b	2438	4938	8.0	16.2
	160 kg N ha^{-1}: 0 kg S ha^{-1}	325ab	3695	7346	11.4	22.7
	160 kg N ha^{-1}: 27 kg S ha^{-1}	349a	4004	7914	11.4	22.7
Conquest (OP§)	Control	307b	1951	4675	6.6	15.6
	160 kg N ha^{-1}: 0 kg S ha^{-1}	316ab	1850	4889	5.9	15.6
	160 kg N ha^{-1}: 27 kg S ha^{-1}	291b	2367	5462	8.1	18.7
Cultivar means						
45H21 (HY)		326	3379a	6733a	10.3a	20.5
Conquest (OP)		304	2056b	5009b	6.8b	16.6
	Fertilizer means					
	Control	306	2195b	4807b	7.3b	15.9b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	320	2772ab	6118ab	8.7ab	19.1ab
	160 kg N ha^{-1}: 27 kg S ha^{-1}	320	3186a	6688a	9.8a	20.7a

ANOVA	df	Evapotranspiration	Seed Yield	Straw Yield	WUEseed	WUEstraw
				$P > F$		
Cultivar	1	0.1477	0.0048*	0.0281*	0.0147*	0.1084
Fertilizer	2	0.3566	0.0258*	0.0315*	0.0825†	0.0943†
Cultivar x Fertilizer	2	0.0318*	0.1062	0.1764	0.1647	0.3105
C.V. (%)		5.5	22.5	23.5	24.6	24.0

‡ HY = Hybrid canola cultivar.

§ OP = Open-pollinated cultivar.

a-b Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

Nitrogen and sulphur accumulation in the 160 kg N ha^{-1}: 27 kg S ha^{-1} treatment was similar to that in the 160 kg N ha^{-1}: 0 kg S ha^{-1} treatment, but greater than that in the control (Table 5.3). There were no significant differences in biomass under any of the three fertilizer treatments; however, the effect of fertilizer treatment on N concentration was almost significant and may be causing the differences in N accumulation with fertilizer addition. The reason for the fertilizer treatment effect on S accumulation is not known, as biomass yield and S concentration were not significantly affected by fertilizer treatment. Once again, there was no interaction between the effects of cultivar and fertilizer treatment on N or S accumulation.

As with the midseason data, the N and S accumulated by each canola cultivar was very high in this experiment. The seed yields observed at this site are much higher than the average canola yield of 2020 kg ha^{-1} for central Manitoba in 2003 (Manitoba Agriculture, Food and Rural Initiatives 2003). When compared to the standard tables for N and S uptake by canola, prorated for the higher yields, the N and S accumulation in this experiment is not unusually high. Canola yielding 3379 kg ha^{-1} typically removes approximately 216 kg N ha^{-1} and 43 kg S ha^{-1}, whereas canola yielding 2056 kg ha^{-1} typically removes 131 kg N ha^{-1} and 26 kg S ha^{-1} (Manitoba Agriculture and Food 2001). Therefore, the N accumulated by each cultivar is within a normal range for canola grown in Manitoba. Both the hybrid and open-pollinated canola cultivars accumulated more S than would be expected based on the standard values for nutrient removal; however, the high concentration of soil-S at this site may have accounted for the relatively large uptake of S.

5.2.3. Root Growth

The differences in the number of roots for the hybrid and open-pollinated cultivars did not follow a consistent pattern (Figure 5.1). Cultivar did not significantly influence root biomass at any of the depths monitored in this experiment (data not presented). The only significant effect of cultivar on root count was at the 80 to 90 cm depth, where root count was greater for the open-pollinated canola cultivar. At the same depth, root count was greatest for the control treatment then the fertilized treatments. In addition, the average root count was lower for the N and S fertilized treatment than for the control and N alone treatments at the 50 to 60 cm soil depth ($P<0.0671$). It is possible that the fertilized canola rooted shallower in response to nutrient enrichment of the surface soil. This observation agrees with the findings of Kamh et al. (2005) and Vos et al. (1998), where N fertilization decreased the root length of oilseed rape. However, the variability in root count measurements for these soil depths was high (C.V. of 112 and 83%). Therefore, these may have been random effects.

5.2.4. Net Water Loss

Despite the apparent lack of difference in rooting depth between the two canola cultivars, there is evidence of a difference in root activity by each cultivar. Between three and six weeks after emergence, the hybrid canola cultivar extracted significantly more water than the open-pollinated cultivar at the 10 to 30 cm, 30 to 50 cm, and 50 to 70 cm soil depths (Figure 5.1). Since root density does not appear to be the reason for higher water extraction, it is possible that transpiration losses alone, from the higher above-ground biomass accumulated by the hybrid canola cultivar, may have driven the increase in water uptake.

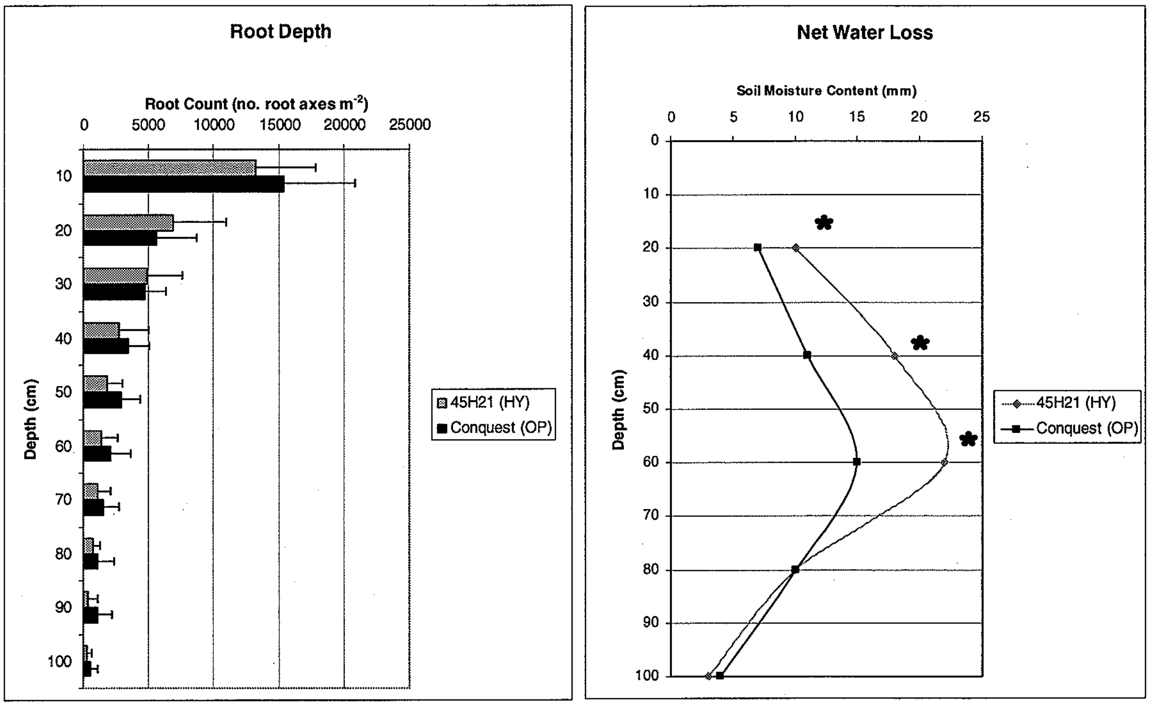

Figure 5.1. Hybrid (HY) and open-pollinated (OP) root count at the 70% bloom stage and Net Water Loss between the six leaf and 70% bloom stages (* indicates cultivar significance).

Net water loss between crop emergence and mature harvest showed a significant difference between water extraction by the two canola cultivars at the 10 to 30 cm and 30 to 50 cm soil depths and nearly significant at 50 to 70 cm (Table 5.5). The hybrid canola cultivar extracted significantly more water from the soil at these depths than the open-pollinated cultivar. For the overall 10 to 110 cm soil depth, there is a significant cultivar by fertilizer interaction, showing that the hybrid cultivar receiving the 160 kg N ha^{-1}: 27 kg S ha^{-1} fertilizer treatment lost 58 more mm of water than the open-pollinated cultivar exposed to the same fertilizer treatment. The larger biomass of the hybrid cultivar

Table 5.5. Net water loss (NWL) between emergence and harvest at the Rosebank-03 site.

Treatment		Soil Depth					
Cultivar	Fertilizer	10-30 cm	30-50 cm	50-70 cm	70-90 cm	90-110 cm	10-110 cm
		NWL (mm)					
45H21 (HY‡)	Control	25	24	31	15c	0	95b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	28	27	32	22bc	6	115ab
	160 kg N ha^{-1}: 27 kg S ha^{-1}	27	24	35	43a	10	139a
Conquest (OP§)	Control	14	20	26	31ab	7	97b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	17	22	23	24bc	19	106ab
	160 kg N ha^{-1}: 27 kg S ha^{-1}	10	15	24	27bc	6	81b
Cultivar means							
45H21 (HY)		27a	25a	33	27	5	116
Conquest (OP)		13b	19b	24	27	11	95
	Fertilizer means						
	Control	19	22	28	23	3	96
	160 kg N ha^{-1}: 0 kg S ha^{-1}	23	25	27	23	13	110
	160 kg N ha^{-1}: 27 kg S ha^{-1}	18	19	29	35	8	110

ANOVA	df	*P* > F					
Cultivar	1	0.0417*	0.0637†	0.1005	0.9479	0.2151	0.1477
Fertilizer	2	0.7714	0.5119	0.8555	0.1213	0.2531	0.3566
Cultivar x Fertilizer	2	0.6327	0.8478	0.6683	0.0144*	0.3044	0.0318*
C.V. (%)		33.8	36.0	32.9	23.8	141.1	16.6

‡ HY = Hybrid canola cultivar.

§ OP = Open-pollinated cultivar.

a-c Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

fertilized with both N and S likely led to greater transpiration losses by the canola, leading to the increase in water loss. There were no differences in water use between the two cultivars under the control or N without S fertilizer treatments.

5.2.5. Evapotranspiration and Water Use Efficiency

There was no statistical difference in evapotranspiration (ET) between the hybrid and open-pollinated cultivars when averaged over the three fertilizer treatments (Table 5.4). However, there was a cultivar by fertilizer interaction indicating that the ET of the hybrid under the 160 kg N ha^{-1}: 27 kg S ha^{-1} treatment was statistically higher than that of the open-pollinated cultivar under the same treatment. This significant interaction is similar to that for the net water loss from the 10 to 110 cm soil depth displayed in Table 5.5, as the net water loss is used to calculate ET.

The water use efficiency (WUE) of the hybrid canola for seed production was greater than that of the open-pollinated cultivar. However, the higher WUE was due to the increased seed yield of the hybrid compared to the open-pollinated cultivar and not due to an overall difference in ET (Table 5.4). A similar explanation can be used for the differences in WUE for the seed and straw seen in the fertilizer group means.

Despite the higher biomass and seed yield of the hybrid cultivar, the lower concentration of N and S of this cultivar lead to similar accumulations of N and S between the hybrid and open-pollinated canola. Similarly, following the 2003 canola harvest, there were no statistically significant differences in the residual NO_3^- and SO_4^{2-} in the 0 to 110 soil depth for either cultivar or fertilizer treatment effects. Therefore, the hybrid cultivar did not appear to consume more N or S than the open-pollinated cultivar. However, due to the variability in residual NO_3-N values (C.V. 37%, Table B.7 in Appendices), a follow crop of wheat was planted in 2004 to extract residual N and S, assuming that the wheat crop would provide a more accurate and precise measure of residual N and S.

5.3. Wheat Crop Experiment 2004

The overall objective of this study was to use a follow crop of wheat to assess the availability of residual N and S after the canola crop experiment.

At mature harvest, the total biomass accumulated by the wheat seeded onto the open-pollinated canola stubble was significantly greater than that seeded onto the hybrid cultivar stubble (Table 5.6). The higher biomass may indicate that there was more N available for removal by the wheat following the open-pollinated canola cultivar. Biomass increases are often associated with an increase in seed yield; therefore, the higher biomass of the wheat seeded to the open-pollinated stubble may also indicate a potential for higher yield. However, although the seed yield of wheat grown on the open-pollinated canola stubble was numerically higher than for the wheat grown on the open-pollinated canola stubble, this effect was not substantial enough to be statistically significant.

The cultivar of the previous canola crop did not affect the N and S concentrations within the wheat plant (Table 5.6). Even with the greater biomass accumulation by the wheat

Table 5.6. Mature harvest grain and biomass yields, whole-plant N and S concentration and N and S accumulations wheat at the Rosebank-04 site.

Treatment: Cultivar	Treatment: Fertilizer	Grain Yield	Total Biomass	N Concentration	S Concentration	N Accumulation	S Accumulation
		--kg ha^{-1}--	--kg ha^{-1}--	----%----	----%----	----kg ha^{-1}----	----kg ha^{-1}----
45H21 (HY‡)	Control	2762	6961	1.26	0.10	87.9	6.8
	160 kg N ha^{-1}: 0 kg S ha^{-1}	2971	7706	1.26	0.10	97.3	8.0
	160 kg N ha^{-1}: 27 kg S ha^{-1}	3057	7683	1.42	0.11	111.0	8.4
Conquest (OP§)	Control	3349	8528	1.26	0.09	106.5	7.9
	160 kg N ha^{-1}: 0 kg S ha^{-1}	3561	9250	1.38	0.11	129.1	10.4
	160 kg N ha^{-1}: 27 kg S ha^{-1}	3492	9456	1.40	0.11	133.3	10.0
Cultivar means							
45H21 (HY)		2930	7450b	1.32	0.10	98.7	7.7
Conquest (OP)		3467	9078a	1.35	0.10	123.0	9.4
	Fertilizer means						
	Control	3056	7744	1.26	0.10	97.2	7.3b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	3266	8478	1.32	0.11	113.2	9.2a
	160 kg N ha^{-1}: 27 kg S ha^{-1}	3275	8569	1.41	0.11	122.2	9.2a
ANOVA	df	$P > F$					
Cultivar	1	0.1524	0.0592†	0.7456	0.9724	0.1304	0.1174
Fertilizer	2	0.6549	0.4067	0.1175	0.1952	0.1286	0.0599†
Cultivar x Fertilizer	2	0.9455	0.9815	0.4056	0.2218	0.8391	0.7140
C.V. (%)		17.9	16.4	7.5	6.4	23.8	17.3

‡ HY = Hybrid canola cultivar.

§ OP = Open-pollinated cultivar.

a-b Mean values followed by the same letter (within columns) are not significantly different.

† Significant at $P < 0.10$.

seeded onto the open-pollinated stubble, the lack of difference in plant tissue N and S concentrations led to a similar lack of response in total N and S accumulated by the wheat crop (Table 5.6). Accumulation of N and S by the wheat seeded on to the open-pollinated canola stubble was numerically higher than that seeded after the hybrid; however, the difference was not significant.

The lack of canola cultivar effect on N and S uptake in the subsequent wheat crop coincides with the residual soil test data, indicating that the hybrid canola cultivar did not consume more N and S than the open-pollinated cultivar. However, these uptake data contradict the observation of increased biomass yield of wheat on the hybrid canola stubble. One possible reason for this discrepancy is that the hybrid canola cultivar may have consumed more water than the open-pollinated cultivar. The hybrid cultivar exposed to the 160 kg N ha^{-1}: 27 kg N ha^{-1} fertilizer treatment removed an extra 58 mm of water from the soil during the growing season. However, during the wheat crop's growing season, the experimental site received above-average precipitation, weakening the strength of this explanation.

Wheat grown on the stubble of canola that had received S fertilizer accumulated more S than wheat grown on stubble where no S was applied in the previous year. Fertilizer S addition also caused an increase in S accumulation by the canola in the previous year. Similar to the response of canola to S fertilization, it is not known why the wheat responded to residual S fertilizer application, as the concentrations of native soil-S at this site are very high.

The total N recovered in the soil and by the wheat seeded onto the open-pollinated canola stubble was numerically greater than that recovered in the soil and by the wheat seeded onto the hybrid stubble (Table 5.7); however, this difference was also not statistically significant. The higher biomass of the wheat grown on the open-pollinated canola stubble created the difference in N recovery, as the bulk of the recoverable N was made up by the total plant N uptake. There was no canola cultivar effect on recoverable S; this was expected because the soil-S reserves at this site were ample for a low-S requiring crop such as wheat.

The lack of difference in N and S recovered in the soil and accumulated by wheat grown on the hybrid and open-pollinated canola stubble confirms the results of the previous canola crop experiment. In 2003, there was no significant difference in the total N and S accumulated by the hybrid and open-pollinated canola cultivars. As well, there was no difference in residual NO_3^- and SO_4^{2-} concentrations in the soil after the canola experiment.

Table 5.7. N and S recovered by wheat crop at mature harvest following canola at the Rosebank-04 site.

Previous Treatment		Residual Soil NO_3-N	Total plant N uptake	Recoverable N[y]	Residual Soil SO_4^{2}-S	Total plant S uptake	Recoverable S[z]
Cultivar	Fertilizer	--------kg ha^{-1}--------					
45H21 (HY[‡])	Control	11.2	87.9	99.1	92.4	6.8	99.2
	160 kg N ha^{-1}: 0 kg S ha^{-1}	18.5	97.3	115.8	69.4	8.0	77.4
	160 kg N ha^{-1}: 27 kg S ha^{-1}	16.8	111.0	127.8	60.5	8.4	68.9
Conquest (OP[§])	Control	12.6	106.5	119.1	121.0	7.9	128.8
	160 kg N ha^{-1}: 0 kg S ha^{-1}	18.5	129.1	147.6	62.2	10.4	72.5
	160 kg N ha^{-1}: 27 kg S ha^{-1}	13.4	133.3	146.7	44.2	10.0	54.2
Cultivar means							
45H21 (HY)		15.5	98.7	114.2	74.1	7.7	81.8
Conquest (OP)		14.8	123.0	137.8	75.8	9.4	85.2
	Fertilizer means						
	Control	11.9	97.2	109.1	106.7	7.3b	114.0
	160 kg N ha^{-1}: 0 kg S ha^{-1}	18.5	113.2	131.7	65.8	9.2a	75.0
	160 kg N ha^{-1}: 27 kg S ha^{-1}	15.1	122.2	137.3	52.4	9.2a	61.5

ANOVA	df	$P > F$					
Cultivar	1	0.8485	0.1304	0.1757	0.9475	0.1174	0.8952
Fertilizer	2	0.3049	0.1286	0.1048	0.2171	0.0599†	0.2443
Cultivar x Fertilizer	2	0.8405	0.8391	0.8557	0.7470	0.7140	0.7575
C.V. (%)		62.5	23.8	22.2	93.2	17.3	85.0

[‡] HY = Hybrid canola cultivar.

[§] OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

† Significant at $P < 0.10$.

[y] Calculated as the sum of soil NO_3-N to 60 cm plus aboveground plant N accumulated at mature harvest.

[z] Calculated as the sum of soil SO_4^{2}-S to 60 cm plus aboveground plant S accumulated at mature harvest.

6. SUMMARY AND CONCLUSIONS

Hybrid canola cultivars, such as 45H21, typically exhibit higher yields than open-pollinated varieties (Brandt et al. 2002; Karamanos et al. 2002; Van Deynze et al. 1992) which may lead to greater uptake of N and S from the soil and/or fertilizer. Researchers have recently reported that hybrid canola does not respond to S fertilizer under circumstances where open-pollinated varieties show an S fertilizer response, even on soils with adequate soil test S (Karamanos et al. 2002). Hybrid varieties may be better at using plant-available S (Deibert et al. 2002), or may be better 'scavengers' for soil nutrients, leading to the increased S-efficiency of these varieties.

The main purpose of this study was to understand the differences in N and S uptake by a hybrid versus an open-pollinated cultivar of canola. However, since only one hybrid and one open-pollinated canola cultivar were used in this experiment, we cannot make firm conclusions about the fertilizer responses of hybrid and open-pollinated cultivars in general.

The first objective of the canola crop experiment was to determine the effects of cultivar and fertilizer treatment on the accumulation of N and S by the two cultivars. While the results showed that the hybrid cultivar accumulated more biomass than the open-pollinated cultivar, the higher tissue N and S concentrations of the open-pollinated cultivar offset this difference; therefore, there was no significant difference in the total N and S accumulated by each cultivar. Based on the hypothesis that hybrids are better 'scavengers' of N and S, we had expected that the hybrid would accumulate a greater amount of each nutrient, especially since they exhibit such a high biomass accumulation. Our experiment did not support this hypothesis. However, given the limitations of a single site year experiment on high-S soil, with only one cultivar for each type of canola, our evidence is not sufficient to disprove this hypothesis, either.

Although the two cultivars accumulated similar amounts of N and S, their efficiency of nutrient use was substantially different. The hybrid canola cultivar achieved a greater yield than the open-pollinated cultivar, in spite of having a lower concentration of S in tissue. Therefore, hybrid canola cultivars may be more efficient at utilizing soil and/or fertilizer S than open-pollinated cultivars allowing the hybrid cultivars to be less dependent on fertilizer S for growth and development.

It is important to note that there was no interaction between cultivar and fertilizer on the response of canola to N and S fertilizer in this experiment. Based on the results of Westco's N:S ratio project, we had expected to see an interaction indicating that each cultivar was responding differently to the fertilizer treatments; however, the Westco experiment was carried out on low-S soils. The background soil S concentrations at this experimental site were high, even for a high S-requiring plant such as canola; therefore, it was surprising that the cultivars responded to the addition of S fertilizer. Still, a site with lower SO_4^{2-}-S may have revealed greater differences in N and S response by the two canola cultivars.

The second objective of the canola crop experiment was to determine if there was a difference in either root distribution or root activity between the two cultivars. We had originally hypothesized that the decreased dependence on S fertilizer by hybrid canola, as shown by Westco's research, may have been due to a deeper rooting habit, allowing the hybrid canola to access subsoil S. Although there was no evidence in this experiment of a difference in root length or biomass between the two cultivars, the hybrid cultivar extracted more water than the open-pollinated cultivar between the 10 and 70 cm soil depths. However, the driving force behind the increase in soil water loss may have simply been higher transpiration rates for the hybrid, as this cultivar had greater biomass and increased leaf area from which to transpire water. Therefore, although root distribution appeared to be similar for these two canola cultivars, root activity likely differed between cultivars. However, as mentioned previously, this difference in water uptake did not contribute to a difference in N and S uptake at this site.

The third objective of this study was to determine the effect of soil-N and -S removal by the two canola cultivars on a subsequent wheat crop. Although the biomass of the wheat seeded on to the open-pollinated stubble was higher than that seeded on to the hybrid stubble, there was no significant differences in seed yield between the cultivar treatments. Therefore, the response of the wheat to the canola cultivar and fertilizer treatments confirmed that these treatments had very little, if any, impact on the supply of residual N and S for the subsequent crop. Overall, the hybrid and open-pollinated canola cultivars appeared to accumulate a similar amount of N and S. Therefore, as expected, there was no significant effect of canola cultivar on the concentration of N and S remaining in the soil after the canola harvest or the accumulation of N and S by the following wheat crop or the concentration of residual N and S after the wheat crop.

Although this study was not able to fully explain why hybrid canola cultivars typically respond less than open-pollinated cultivars to the addition of S fertilizer, a few important observations deserve to be highlighted. First, the hybrid cultivar in this experiment had a lower tissue concentration of N and S, which may indicate greater efficiency in utilizing these nutrients. Second, the hybrid canola cultivar exhibited greater water loss than the open-pollinated cultivar between the six-leaf and 70% bloom stages. This appeared to be due mostly to greater transpiration rates from the larger crop surface, but the moisture removed by this cultivar may have implications for the subsequent crop, especially if the season following the canola is dry.

Future research into this area of study should include a greater number of hybrid and open-pollinated canola varieties; this would allow for stronger conclusions about hybrid and open-pollinated cultivars. As well, it would be beneficial to carry out a more in-depth look at the effect of different rates of N and S on these cultivars. The optimum rate of N and S for a given cultivar of canola varies with site conditions such as moisture supply and soil reserves of N and S. Therefore, our approach of using one pre-selected rate of N and one pre-selected rate of S may have resulted in luxuriously large applications of both nutrients, well in excess of agronomic requirements for either cultivar. Applying N and S at several rates may have allowed subtle differences in the cultivars' fertilizer response to be more apparent.

Finally, the most important need for additional research is to conduct this type of experiment on soils testing low in S. The high concentrations of soil test-S at the Rosebank site were greater than that required for canola production; therefore, we were not able to test the response of the canola cultivars to fertilizer treatments within an S-limiting environment. Carrying out a similar experiment on a low-S soil, using a greater number of hybrid and open-pollinated cultivars, would create a better understanding of the mechanism by which hybrid canola cultivars utilize S and allow producers to make more informed agronomic decisions with regards to hybrid canola production.

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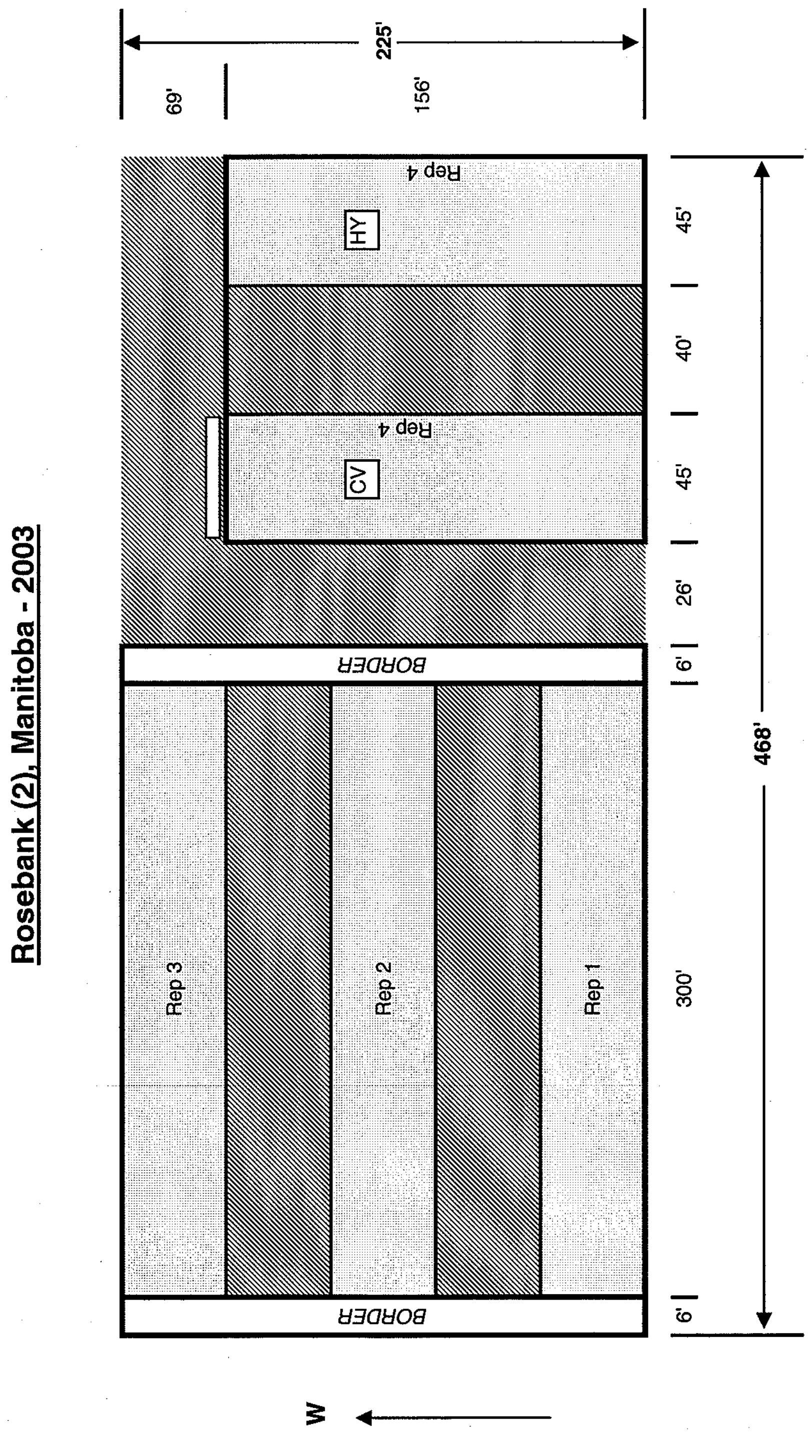
8.0 APPENDICES

8.1 APPENDIX A – SITE LAYOUT FOR THE CANOLA AND WHEAT CROP EXPERIMENTS AT ROSEBANK, MANITOBA



N:S Ratios (Hybrid and Conventional Canola Cultivars)

Spring 2003 Field Sheet (Hoedrill)

Test #: ____________

Location: Rosebank (2), MB

\| 6' \|

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
45'	13	1	1	4	9	14	7	12	18	5	5	17	6	2	20	21	15	15	8	16	19	10	3	11	BORDER	BORDER	40	39	35	27	24	26	26	34	29	23	31	32	25	28	36	36	37	42	30	33	22	22	41	38	33
	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY			CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV
	80	---	---	120	120	120	40	40	80	160	160	40	200	40	160	200	160	160	80	200	120	160	80	200			120	80	120	200	80	160	160	80	80	40	160	200	120	40	160	160	200	200	120	40	---	---	160	40	40
	13	---	---	---	80	20	27	7	7	---	---	3	---	---	13	17	27	27	53	33	10	107	---	133			10	7	20	---	---	---	---	13	53	---	107	133	---	27	27	27	33	17	80	7	---	---	13	3	7
	27	35	28	32	34	40	25	38	41	37	42	31	33	36	26	24	26	36	29	22	22	23	30	39	24	BORDER	10	2	21	15	15	19	1	1	12	16	9	4	11	17	14	13	3	20	6	8	5	5	18	7	
W ↑	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV		HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	
	200	120	40	200	80	120	120	40	160	200	200	160	40	160	160	80	160	160	80	---	---	40	120	80	80		160	40	200	160	160	120	---	---	40	200	120	120	200	40	120	80	80	160	200	80	160	160	80	40	
	---	20	27	133	13	10	---	3	13	33	17	107	7	27	---	---	---	27	53	---	---	---	80	7	---		107	---	17	27	27	10	---	---	7	33	80	---	133	3	20	13	---	13	---	53	---	---	7	27	
	2	13	15	15	17	6	18	20	11	21	12	8	4	10	16	7	5	5	14	3	1	1	9	19	BORDER	34	37	26	26	35	39	32	33	25	22	22	40	23	41	42	27	30	34	36	36	38	31	29	28	24	
	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY		CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	
	40	80	160	160	40	200	80	160	200	200	40	80	120	160	200	40	160	160	120	80	---	---	120	120		80	200	160	160	120	80	200	40	120	---	---	120	40	160	200	200	120	80	160	160	40	160	80	40	80	
	---	13	27	27	3	---	7	13	133	17	7	53	---	107	33	27	---	---	20	---	---	---	80	10		13	33	---	---	20	7	133	7	---	---	---	10	---	13	17	---	80	13	27	27	3	107	53	27	---	
Trt >	1	1	2	3	4	5	5	6	7	8	9	10	11	12	13	14	15	15	16	17	18	19	20	21	BORDER	30	22	22	23	24	25	26	26	27	28	29	30	31	32	33	34	35	36	36	37	38	39	40	41	42	
Var >	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY		CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	CV	
N >	---	---	40	80	120	160	160	200	40	80	120	160	200	40	80	120	160	160	200	40	80	120	160	200		120	---	---	40	80	120	160	160	200	40	80	120	160	200	40	80	120	160	160	200	40	80	120	160	200	
S >	---	---	---	---	---	---	---	---	27	53	80	107	133	7	13	20	27	27	33	3	7	10	13	17		80	---	---	---	---	---	---	---	---	27	53	80	107	133	7	13	20	27	27	33	3	7	10	13	17	
Run >>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	

Treatment Description

N:S Ratio	Trt	N	S, Cultivar	Trt	N	S, Cultivar
	1	0 kg N/ha,	0 kg S/ha, Hybrid Cultivar 1 (HY)	22	0 kg N/ha,	0 kg S/ha, Conventional Cultivar 1 (CV)
	2	40 kg N/ha,	0 kg S/ha, Hybrid Cultivar 1 (HY)	23	40 kg N/ha,	0 kg S/ha, Conventional Cultivar 1 (CV)
	3	80 kg N/ha,	0 kg S/ha, Hybrid Cultivar 1 (HY)	24	80 kg N/ha,	0 kg S/ha, Conventional Cultivar 1 (CV)
	4	120 kg N/ha,	0 kg S/ha, Hybrid Cultivar 1 (HY)	25	120 kg N/ha,	0 kg S/ha, Conventional Cultivar 1 (CV)
	5	160 kg N/ha,	0 kg S/ha, Hybrid Cultivar 1 (HY)	26	160 kg N/ha,	0 kg S/ha, Conventional Cultivar 1 (CV)
	6	200 kg N/ha,	0 kg S/ha, Hybrid Cultivar 1 (HY)	27	200 kg N/ha,	0 kg S/ha, Conventional Cultivar 1 (CV)
1.5:1	7	40 kg N/ha,	26.7 kg S/ha, Hybrid Cultivar 1 (HY)	28	40 kg N/ha,	26.7 kg S/ha, Conventional Cultivar 1 (CV)
	8	80 kg N/ha,	53.3 kg S/ha, Hybrid Cultivar 1 (HY)	29	80 kg N/ha,	53.3 kg S/ha, Conventional Cultivar 1 (CV)
	9	120 kg N/ha,	80.0 kg S/ha, Hybrid Cultivar 1 (HY)	30	120 kg N/ha,	80.0 kg S/ha, Conventional Cultivar 1 (CV)
	10	160 kg N/ha,	106.7 kg S/ha, Hybrid Cultivar 1 (HY)	31	160 kg N/ha,	106.7 kg S/ha, Conventional Cultivar 1 (CV)
	11	200 kg N/ha,	133.3 kg S/ha, Hybrid Cultivar 1 (HY)	32	200 kg N/ha,	133.3 kg S/ha, Conventional Cultivar 1 (CV)
6:1	12	40 kg N/ha,	6.7 kg S/ha, Hybrid Cultivar 1 (HY)	33	40 kg N/ha,	6.7 kg S/ha, Conventional Cultivar 1 (CV)
	13	80 kg N/ha,	13.3 kg S/ha, Hybrid Cultivar 1 (HY)	34	80 kg N/ha,	13.3 kg S/ha, Conventional Cultivar 1 (CV)
	14	120 kg N/ha,	20.0 kg S/ha, Hybrid Cultivar 1 (HY)	35	120 kg N/ha,	20.0 kg S/ha, Conventional Cultivar 1 (CV)
	15	160 kg N/ha,	26.7 kg S/ha, Hybrid Cultivar 1 (HY)	36	160 kg N/ha,	26.7 kg S/ha, Conventional Cultivar 1 (CV)
	16	200 kg N/ha,	33.3 kg S/ha, Hybrid Cultivar 1 (HY)	37	200 kg N/ha,	33.3 kg S/ha, Conventional Cultivar 1 (CV)
12:1	17	40 kg N/ha,	3.3 kg S/ha, Hybrid Cultivar 1 (HY)	38	40 kg N/ha,	3.3 kg S/ha, Conventional Cultivar 1 (CV)
	18	80 kg N/ha,	6.7 kg S/ha, Hybrid Cultivar 1 (HY)	39	80 kg N/ha,	6.7 kg S/ha, Conventional Cultivar 1 (CV)
	19	120 kg N/ha,	10.0 kg S/ha, Hybrid Cultivar 1 (HY)	40	120 kg N/ha,	10.0 kg S/ha, Conventional Cultivar 1 (CV)
	20	160 kg N/ha,	13.3 kg S/ha, Hybrid Cultivar 1 (HY)	41	160 kg N/ha,	13.3 kg S/ha, Conventional Cultivar 1 (CV)
	21	200 kg N/ha,	16.7 kg S/ha, Hybrid Cultivar 1 (HY)	42	200 kg N/ha,	16.7 kg S/ha, Conventional Cultivar 1 (CV)

Application Instructions

nutrient	source	placement	rate (kg nutrient/ha)
N (1)	46-0-0	SB	variable
N (2)	20.5-0-0-24	SB	variable
P2O5	0-45-0	SR	25
K2O	0-0-60	SB	30
S	20.5-0-0-24	SB	variable

	MB
Hybrid Cultivar:	45H21
Conventional Cultivar:	Conquest

8.2 APPENDIX B – RECOMMENDATIONS FOR FIELD STUDIES ON ROOT ACTIVITY

In addition to the limitations outlined in the discussion on page 63, the following recommendations should be considered by students wishing to study root systems:

1. Avoid fields with shallow depth to an impermeable layer which may restrict root depth and/or water percolation. The site near Thornhill, Manitoba had a dense layer of shale gravel below 60 to 70 cm which created difficulties in removing soil cores to a depth of 120 cm, as was originally planned. As well, the perched water table below 70 cm hindered our ability to effectively measure changes in soil moisture at depth. Therefore, during the site selection process, it is important that a field site be characterized to the depth at which sampling will occur.

2. Increase the number of root cores removed per plot to decrease the variability of the results. The C.V. of the root count data in this study ranged from 26 to 124%. Only one core was removed per plot; however, had a greater number of cores been removed, the root count variability may have been limited.

8.3 APPENDIX C – ANALYSIS OF VARIANCE AND LEAST SQUARED MEANS FOR THE EFFECTS OF CULTIVAR AND FERTILIZER NITROGEN AND SULPHUR TREATMENTS ON SOIL NITRATE AND SULPHATE CONTENT AT THE 2003 ROSEBANK EXPERIMENTAL SITE

Table C.1. Soil NO_3^- content (kg ha^{-1}) of the 0-10 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Preseed	Midseason	Harvest
		kg ha^{-1}		
45H21 (HY‡)	Control	71	4	11c
	160 kg N ha^{-1}: 0 kg S ha^{-1}	35	6	28bc
	160 kg N ha^{-1}: 27 kg S ha^{-1}	39	7	19bc
Conquest (OP§)	Control	39	5	11c
	160 kg N ha^{-1}: 0 kg S ha^{-1}	41	8	34b
	160 kg N ha^{-1}: 27 kg S ha^{-1}	29	16	65a
Cultivar means				
45H21 (HY)		48	6b	20b
Conquest (OP)		37	10a	37a
	Fertilizer means			
	Control	55	5	11b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	38	7	31a
	160 kg N ha^{-1}: 27 kg S ha^{-1}	34	12	42a

ANOVA	df		$P > F$	
Cultivar	1	0.2955	0.0725†	0.0027*
Fertilizer	2	0.2655	0.2100	0.0282*
Cultivar x Fertilizer	2	0.3759	0.2250	0.0029*
C.V. (%)		71.6	64.6	29.8

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-c] Mean values followed by the same letter (within columns) are not significantly different.
* Significant at $P < 0.05$.
† Significant at $P < 0.10$.

Table C.2. Soil NO_3^- content (kg ha^{-1}) of the 10-30 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Preseed	Midseason	Harvest
		--kg ha^{-1}--		
45H21 (HY‡)	Control	29	3b	18
	160 kg N ha^{-1}: 0 kg S ha^{-1}	18	22b	39
	160 kg N ha^{-1}: 27 kg S ha^{-1}	29	25b	43
Conquest (OP§)	Control	22	8b	17
	160 kg N ha^{-1}: 0 kg S ha^{-1}	23	29b	35
	160 kg N ha^{-1}: 27 kg S ha^{-1}	21	83a	75
Cultivar means				
45H21 (HY)		25	17b	33
Conquest (OP)		22	40a	42
	Fertilizer means			
	Control	26	6b	18b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	21	26ab	37ab
	160 kg N ha^{-1}: 27 kg S ha^{-1}	25	54a	59a

ANOVA	df		$P > F$	
Cultivar	1	0.5120	0.0143*	0.2842
Fertilizer	2	0.6993	0.0630†	0.0496*
Cultivar x Fertilizer	2	0.5861	0.0361*	0.1730
C.V. (%)		52.4	62.0	44.2

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

Table C.3. Soil NO_3^- content (kg ha^{-1}) of the 30-50 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Preseed	Midseason	Harvest
		-kg ha^{-1}-		
45H21 (HY‡)	Control	17	2	9
	160 kg N ha^{-1}: 0 kg S ha^{-1}	10	15	15
	160 kg N ha^{-1}: 27 kg S ha^{-1}	14	14	17
Conquest (OP§)	Control	23	5	6
	160 kg N ha^{-1}: 0 kg S ha^{-1}	17	12	18
	160 kg N ha^{-1}: 27 kg S ha^{-1}	17	18	21
Cultivar means				
45H21 (HY)		14	10	14
Conquest (OP)		19	12	15
	Fertilizer means			
	Control	20	3	8
	160 kg N ha^{-1}: 0 kg S ha^{-1}	13	14	16
	160 kg N ha^{-1}: 27 kg S ha^{-1}	16	16	19

ANOVA	df	$P > F$		
Cultivar	1	0.2365	0.6796	0.7860
Fertilizer	2	0.5718	0.1426	0.2612
Cultivar x Fertilizer	2	0.9443	0.6953	0.8226
C.V. (%)		74.0	76.4	60.7

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

Table C.4. Soil NO_3^- content (kg ha^{-1}) of the 50-70 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Preseed	Midseason	Harvest
		--kg ha^{-1}--		
45H21 (HY‡)	Control	10	7	6
	160 kg N ha^{-1}: 0 kg S ha^{-1}	10	9	6
	160 kg N ha^{-1}: 27 kg S ha^{-1}	9	8	7
Conquest (OP§)	Control	11	4	5
	160 kg N ha^{-1}: 0 kg S ha^{-1}	15	7	8
	160 kg N ha^{-1}: 27 kg S ha^{-1}	13	8	9
Cultivar means				
45H21 (HY)		10	8	6
Conquest (OP)		13	6	7
	Fertilizer means			
	Control	11	6	6
	160 kg N ha^{-1}: 0 kg S ha^{-1}	12	8	7
	160 kg N ha^{-1}: 27 kg S ha^{-1}	11	8	8

ANOVA	df		$P > F$	
Cultivar	1	0.1479	0.3663	0.5384
Fertilizer	2	0.8383	0.6523	0.6069
Cultivar x Fertilizer	2	0.7339	0.8550	0.7306
C.V. (%)		53.0	85.7	62.2

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

Table C.5. Soil NO_3^- content (kg ha^{-1}) of the 70-90 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Preseed	Midseason	Harvest
		kg ha^{-1}		
45H21 (HY‡)	Control	14	12	9
	160 kg N ha^{-1}: 0 kg S ha^{-1}	13	13	7
	160 kg N ha^{-1}: 27 kg S ha^{-1}	8	7	7
Conquest (OP§)	Control	12	13	6
	160 kg N ha^{-1}: 0 kg S ha^{-1}	16	11	8
	160 kg N ha^{-1}: 27 kg S ha^{-1}	9	8	10
Cultivar means				
45H21 (HY)		12	10	8
Conquest (OP)		12	11	8
	Fertilizer means			
	Control	13	12	8
	160 kg N ha^{-1}: 0 kg S ha^{-1}	15	12	8
	160 kg N ha^{-1}: 27 kg S ha^{-1}	9	7	9

ANOVA	df		$P > F$	
Cultivar	1	0.8356	0.9550	0.9280
Fertilizer	2	0.2011	0.4562	0.9240
Cultivar x Fertilizer	2	0.7444	0.9274	0.6915
C.V. (%)		62.5	93.4	70.3

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.

Table C.6. Soil NO_3^- content (kg ha^{-1}) of the 90-110 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Preseed	Midseason	Harvest
		-----------------------	kg ha^{-1}	-----------------------
45H21 (HY‡)	Control	13	13	12
	160 kg N ha^{-1}: 0 kg S ha^{-1}	15	10	11
	160 kg N ha^{-1}: 27 kg S ha^{-1}	11	7	15
Conquest (OP§)	Control	29	13	7
	160 kg N ha^{-1}: 0 kg S ha^{-1}	18	8	14
	160 kg N ha^{-1}: 27 kg S ha^{-1}	15	14	13
Cultivar means				
45H21 (HY)		13b	10	12
Conquest (OP)		21a	12	12
	Fertilizer means			
	Control	21a	13	9
	160 kg N ha^{-1}: 0 kg S ha^{-1}	17ab	9	12
	160 kg N ha^{-1}: 27 kg S ha^{-1}	13b	10	14

ANOVA	df		$P > F$	
Cultivar	1	0.0086*	0.4491	0.8224
Fertilizer	2	0.0523†	0.4715	0.6026
Cultivar x Fertilizer	2	0.0939†	0.3169	0.6695
C.V. (%)		44.6	65.1	88.0

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-b] Mean values followed by the same letter (within columns) are not significantly different.
* Significant at $P < 0.05$.
† Significant at $P < 0.10$.

Table C.7. Soil NO_3^- content (kg ha^{-1}) of the 0-110 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Preseed	Midseason	Harvest
		-----------------------kg ha^{-1}-----------------------		
45H21 (HY‡)	Control	154	40b	64
	160 kg N ha^{-1}: 0 kg S ha^{-1}	101	78b	109
	160 kg N ha^{-1}: 27 kg S ha^{-1}	109	69b	111
Conquest (OP§)	Control	137	49b	54
	160 kg N ha^{-1}: 0 kg S ha^{-1}	130	74b	116
	160 kg N ha^{-1}: 27 kg S ha^{-1}	104	146a	192
Cultivar means				
45H21 (HY)		122	62b	95
Conquest (OP)		124	90a	121
	Fertilizer means			
	Control	146	44	59b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	116	76	112ab
	160 kg N ha^{-1}: 27 kg S ha^{-1}	107	108	152a

ANOVA	df		$P > F$	
Cultivar	1	0.9375	0.0662†	0.2155
Fertilizer	2	0.3779	0.1401	0.0677†
Cultivar x Fertilizer	2	0.6989	0.0703†	0.1741
C.V. (%)		55.8	41.2	37.4

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-b] Mean values followed by the same letter (within columns) are not significantly different.
† Significant at $P < 0.10$.

Table C.8. Soil SO_4^{2-} content (kg ha^{-1}) of the 0-10 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Preseed	Midseason	Harvest
		----------kg ha^{-1}----------		
45H21 (HY‡)	Control	30	9	33
	160 kg N ha^{-1}: 0 kg S ha^{-1}	20	10	21
	160 kg N ha^{-1}: 27 kg S ha^{-1}	20	5	22
Conquest (OP§)	Control	25	8	26
	160 kg N ha^{-1}: 0 kg S ha^{-1}	21	11	27
	160 kg N ha^{-1}: 27 kg S ha^{-1}	29	11	31
Cultivar means				
45H21 (HY)		23	8	26
Conquest (OP)		25	10	28
	Fertilizer means			
	Control	27	9	30
	160 kg N ha^{-1}: 0 kg S ha^{-1}	20	11	24
	160 kg N ha^{-1}: 27 kg S ha^{-1}	25	8	26

ANOVA	df		*P* > F	
Cultivar	1	0.5537	0.3375	0.7448
Fertilizer	2	0.1680	0.4928	0.8538
Cultivar x Fertilizer	2	0.1929	0.1929	0.6327
C.V. (%)		30.0	31.2	60.1

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

Table C.9. Soil SO_4^{2-} content (kg ha^{-1}) of the 10-30 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Preseed	Midseason	Harvest
		kg ha^{-1}		
45H21 (HY‡)	Control	29	9	66
	160 kg N ha^{-1}: 0 kg S ha^{-1}	25	23	30
	160 kg N ha^{-1}: 27 kg S ha^{-1}	27	15	32
Conquest (OP§)	Control	38	16	69
	160 kg N ha^{-1}: 0 kg S ha^{-1}	29	44	65
	160 kg N ha^{-1}: 27 kg S ha^{-1}	38	32	70
Cultivar means				
45H21 (HY)		27	16	43
Conquest (OP)		35	31	68
	Fertilizer means			
	Control	33	13	68
	160 kg N ha^{-1}: 0 kg S ha^{-1}	27	34	47
	160 kg N ha^{-1}: 27 kg S ha^{-1}	32	24	51

ANOVA	df		$P > F$	
Cultivar	1	0.1917	0.1446	0.1197
Fertilizer	2	0.5654	0.3947	0.7654
Cultivar x Fertilizer	2	0.8408	0.8431	0.5691
C.V. (%)		35.1	95.1	61.1

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

Table C.10. Soil SO_4^{2-} content (kg ha^{-1}) of the 30-50 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Preseed	Midseason	Harvest
		kg ha^{-1}		
45H21 (HY‡)	Control	50	17	61
	160 kg N ha^{-1}: 0 kg S ha^{-1}	24	13	31
	160 kg N ha^{-1}: 27 kg S ha^{-1}	31	11	54
Conquest (OP§)	Control	39	37	63
	160 kg N ha^{-1}: 0 kg S ha^{-1}	86	73	93
	160 kg N ha^{-1}: 27 kg S ha^{-1}	52	29	83
Cultivar means				
45H21 (HY)		35	14b	49
Conquest (OP)		59	46a	80
	Fertilizer means			
	Control	45	27	62
	160 kg N ha^{-1}: 0 kg S ha^{-1}	55	43	62
	160 kg N ha^{-1}: 27 kg S ha^{-1}	41	20	69

ANOVA	df		*P* > F	
Cultivar	1	0.1476	0.0511†	0.3018
Fertilizer	2	0.7712	0.6340	0.9801
Cultivar x Fertilizer	2	0.1899	0.4745	0.5897
C.V. (%)		83.3	110.3	78.1

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

† Significant at *P* < 0.10.

Table C.11. Soil SO_4^{2-} content (kg ha^{-1}) of the 50-70 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Preseed	Midseason	Harvest
		----------kg ha^{-1}----------		
45H21 (HY‡)	Control	86abc	72	81
	160 kg N ha^{-1}: 0 kg S ha^{-1}	60bc	89	66
	160 kg N ha^{-1}: 27 kg S ha^{-1}	30c	49	71
Conquest (OP§)	Control	59bc	64	86
	160 kg N ha^{-1}: 0 kg S ha^{-1}	141a	136	123
	160 kg N ha^{-1}: 27 kg S ha^{-1}	92ab	35	98
Cultivar means				
45H21 (HY)		59	70	73
Conquest (OP)		97	78	102
	Fertilizer means			
	Control	72	68	84
	160 kg N ha^{-1}: 0 kg S ha^{-1}	100	112	95
	160 kg N ha^{-1}: 27 kg S ha^{-1}	61	42	84

ANOVA	df		$P > F$	
Cultivar	1	0.1655	0.7440	0.4161
Fertilizer	2	0.2433	0.2312	0.9508
Cultivar x Fertilizer	2	0.0761†	0.3478	0.7512
C.V. (%)		68.8	52.0	69.7

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

† Significant at $P < 0.10$.

Table C.12. Soil SO_4^{2-} content (kg ha^{-1}) of the 70-90 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Preseed	Midseason	Harvest
		kg ha^{-1}		
45H21 (HY‡)	Control	122	139	133
	160 kg N ha^{-1}: 0 kg S ha^{-1}	155	179	158
	160 kg N ha^{-1}: 27 kg S ha^{-1}	99	81	79
Conquest (OP§)	Control	102	122	124
	160 kg N ha^{-1}: 0 kg S ha^{-1}	153	156	146
	160 kg N ha^{-1}: 27 kg S ha^{-1}	104	67	105
Cultivar means				
45H21 (HY)		125	133	123
Conquest (OP)		120	115	125
	Fertilizer means			
	Control	112	131a	128
	160 kg N ha^{-1}: 0 kg S ha^{-1}	154	168a	152
	160 kg N ha^{-1}: 27 kg S ha^{-1}	101	74b	92

ANOVA	df		$P > F$	
Cultivar	1	0.8294	0.4801	0.9609
Fertilizer	2	0.2321	0.0212*	0.2891
Cultivar x Fertilizer	2	0.8426	0.9892	0.8512
C.V. (%)		36.5	53.4	66.1

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-b] Mean values followed by the same letter (within columns) are not significantly different.
* Significant at $P < 0.05$.

Table C.13. Soil SO_4^{2-} content (kg ha^{-1}) of the 90-110 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Preseed	Midseason	Harvest
		kg ha^{-1}		
45H21 (HY‡)	Control	153	168	144
	160 kg N ha^{-1}: 0 kg S ha^{-1}	156	179	179
	160 kg N ha^{-1}: 27 kg S ha^{-1}	177	149	133
Conquest (OP§)	Control	141	149	144
	160 kg N ha^{-1}: 0 kg S ha^{-1}	164	165	158
	160 kg N ha^{-1}: 27 kg S ha^{-1}	130	176	152
Cultivar means				
45H21 (HY)		162	166	152
Conquest (OP)		145	163	151
	Fertilizer means			
	Control	147	159	144
	160 kg N ha^{-1}: 0 kg S ha^{-1}	160	172	168
	160 kg N ha^{-1}: 27 kg S ha^{-1}	154	163	143

ANOVA	df		*P* > F	
Cultivar	1	0.6006	0.8998	0.9781
Fertilizer	2	0.7825	0.8005	0.6047
Cultivar x Fertilizer	2	0.3457	0.4874	0.7752
C.V. (%)		24.2	26.5	37.7

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

Table C.14. Soil SO_4^{2-} content (kg ha^{-1}) of the 0-110 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Preseed	Midseason	Harvest
			kg ha^{-1}	
45H21 (HY‡)	Control	470	403	519
	160 kg N ha^{-1}: 0 kg S ha^{-1}	439	498	493
	160 kg N ha^{-1}: 27 kg S ha^{-1}	384	312	389
Conquest (OP§)	Control	403	403	511
	160 kg N ha^{-1}: 0 kg S ha^{-1}	594	580	605
	160 kg N ha^{-1}: 27 kg S ha^{-1}	446	348	538
Cultivar means				
45H21 (HY)		431	405	467
Conquest (OP)		481	444	551
	Fertilizer means			
	Control	437	403	515
	160 kg N ha^{-1}: 0 kg S ha^{-1}	517	539	549
	160 kg N ha^{-1}: 27 kg S ha^{-1}	415	330	464

ANOVA	df		$P > F$	
Cultivar	1	0.6206	0.5569	0.4777
Fertilizer	2	0.3555	0.1795	0.8746
Cultivar x Fertilizer	2	0.3307	0.8778	0.8466
C.V. (%)		32.9	35.1	52.1

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.

8.4 APPENDIX D – ANALYSIS OF VARIANCE AND LEAST SQUARED MEANS FOR THE EFFECTS OF CULTIVAR AND FERTILIZER NITROGEN AND SULPHUR TREATMENTS ON SOIL MOISTURE CONTENT AT THE 2003 ROSEBANK EXPERIMENTAL SITE

Table D.1. Soil water content of the 10-30 cm soil depth at the Rosebank-03 site.

Treatment: Cultivar	Treatment: Fertilizer	Emergence	3WAE¶	6WAE	9WAE	12WAE
		SWC (mm)				
45H21 (HY‡)	Control	70	75	65	49	45
	160 kg N ha^{-1}: 0 kg S ha^{-1}	69	73	61	41	41
	160 kg N ha^{-1}: 27 kg S ha^{-1}	67	69	61	43	40
Conquest (OP§)	Control	70	78	71	61	57
	160 kg N ha^{-1}: 0 kg S ha^{-1}	74	73	65	59	57
	160 kg N ha^{-1}: 27 kg S ha^{-1}	72	77	73	63	62
Cultivar means						
45H21 (HY)		69	72	62b	44b	42b
Conquest (OP)		72	76	69a	61a	58a
	Fertilizer means					
	Control	70	76	68	55	51
	160 kg N ha^{-1}: 0 kg S ha^{-1}	71	73	63	50	49
	160 kg N ha^{-1}: 27 kg S ha^{-1}	69	73	67	53	51

ANOVA	df	$P > F$				
Cultivar	1	0.3266	0.3373	0.0977†	0.0228*	0.0155*
Fertilizer	2	0.6964	0.7030	0.5128	0.6847	0.9353
Cultivar x Fertilizer	2	0.5656	0.7080	0.5680	0.5328	0.3961
C.V. (%)		6.8	12.9	13.6	13.9	14.7

¶ Weeks after emergence.

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

a-b Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

Table D.2. Soil water content of the 30-50 cm soil depth at the Rosebank-03 site.

Treatment						
Cultivar	Fertilizer	Emergence	3WAE¶	6WAE	9WAE	12WAE
		SWC (mm)				
45H21 (HY‡)	Control	63	69	58	41	41
	160 kg N ha^{-1}: 0 kg S ha^{-1}	63	68	43	39	36
	160 kg N ha^{-1}: 27 kg S ha^{-1}	61	71	55	40	37
Conquest (OP§)	Control	70	79	67	54	50
	160 kg N ha^{-1}: 0 kg S ha^{-1}	74	81	70	53	52
	160 kg N ha^{-1}: 27 kg S ha^{-1}	69	79	67	58	54
Cultivar means						
45H21 (HY)		62b	70b	52b	40b	38b
Conquest (OP)		71a	79a	68a	55a	52a
	Fertilizer means					
	Control	67	74	62	48	46
	160 kg N ha^{-1}: 0 kg S ha^{-1}	68	75	56	46	44
	160 kg N ha^{-1}: 27 kg S ha^{-1}	65	75	61	49	46

ANOVA	df	P > F				
Cultivar	1	0.0292*	0.0213*	0.0301*	0.0413*	0.0301*
Fertilizer	2	0.4282	0.9055	0.4768	0.7350	0.8718
Cultivar x Fertilizer	2	0.2132	0.1170	0.2112	0.8053	0.6025
C.V. (%)		2.7	2.5	17.0	13.1	17.8

¶ Weeks after emergence.

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

Table D.3. Soil water content of the 50-70 cm soil depth at the Rosebank-03 site.

Treatment: Cultivar	Treatment: Fertilizer	Emergence	3WAE¶	6WAE	9WAE	12WAE
		SWC (mm)				
45H21 (HY‡)	Control	68	80	58	40b	37
	160 kg N ha^{-1}: 0 kg S ha^{-1}	70	84	63	47a	39
	160 kg N ha^{-1}: 27 kg S ha^{-1}	68	82	60	37b	33
Conquest (OP§)	Control	72	84	67	53a	46
	160 kg N ha^{-1}: 0 kg S ha^{-1}	74	84	69	54a	51
	160 kg N ha^{-1}: 27 kg S ha^{-1}	71	84	72	56a	47
Cultivar means						
45H21 (HY)		69	82	60b	42b	36b
Conquest (OP)		72	84	69a	54a	48a
	Fertilizer means					
	Control	70	82	63	47	42
	160 kg N ha^{-1}: 0 kg S ha^{-1}	72	84	66	51	45
	160 kg N ha^{-1}: 27 kg S ha^{-1}	69	83	66	47	40

ANOVA	df	*P* > F				
Cultivar	1	0.3057	0.3984	0.0253*	0.0543†	0.0856†
Fertilizer	2	0.3261	0.7372	0.1977	0.2502	0.3968
Cultivar x Fertilizer	2	0.9653	0.5533	0.1137	0.0973†	0.7461
C.V. (%)		5.4	5.6	3.5	11.8	20.9

¶ Weeks after emergence.
‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-b] Mean values followed by the same letter (within columns) are not significantly different.
* Significant at $P < 0.05$.
† Significant at $P < 0.10$.

Table D.4. Soil water content of the 70-90 cm soil depth at the Rosebank-03 site.

Treatment: Cultivar	Treatment: Fertilizer	Emergence	3WAE¶	6WAE	9WAE	12WAE
		SWC (mm)				
45H21 (HY‡)	Control	86	95	88	69	71a
	160 kg N ha^{-1}: 0 kg S ha^{-1}	84	93	85	77	62ab
	160 kg N ha^{-1}: 27 kg S ha^{-1}	84	91	78	50	41c
Conquest (OP§)	Control	83	92	82	61	52bc
	160 kg N ha^{-1}: 0 kg S ha^{-1}	86	93	83	71	62ab
	160 kg N ha^{-1}: 27 kg S ha^{-1}	80	91	82	60	53bc
Cultivar means						
45H21 (HY)		85	93	84	65	58
Conquest (OP)		83	92	82	64	56
	Fertilizer means					
	Control	85	93	85	65ab	62
	160 kg N ha^{-1}: 0 kg S ha^{-1}	85	93	84	74a	62
	160 kg N ha^{-1}: 27 kg S ha^{-1}	82	91	80	55b	47

ANOVA	df			*P* > F		
Cultivar	1	0.1897	0.3540	0.6120	0.6931	0.6718
Fertilizer	2	0.5046	0.3796	0.2781	0.0354*	0.1474
Cultivar x Fertilizer	2	0.2891	0.6122	0.3444	0.2205	0.0987†
C.V. (%)		5.2	5.0	8.8	13.3	17.1

¶ Weeks after emergence.
‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-c] Mean values followed by the same letter (within columns) are not significantly different.
* Significant at $P < 0.05$.
† Significant at $P < 0.10$.

Table D.5. Soil water content of the 90-110 cm soil depth at the Rosebank-03 site.

Treatment						
Cultivar	Fertilizer	Emergence	3WAE¶	6WAE	9WAE	12WAE
		SWC (mm)				
45H21 (HY‡)	Control	93	101	99	96	93
	160 kg N ha^{-1}: 0 kg S ha^{-1}	95	102	99	95	89
	160 kg N ha^{-1}: 27 kg S ha^{-1}	93	100	96	90	83
Conquest (OP§)	Control	90	99	94	89	83
	160 kg N ha^{-1}: 0 kg S ha^{-1}	89	96	92	85	70
	160 kg N ha^{-1}: 27 kg S ha^{-1}	87	97	93	81	81
Cultivar means						
45H21 (HY)		93a	101a	98a	94a	88a
Conquest (OP)		89b	97b	93b	85b	78b
	Fertilizer means					
	Control	91	100	96	93	88
	160 kg N ha^{-1}: 0 kg S ha^{-1}	92	99	96	90	79
	160 kg N ha^{-1}: 27 kg S ha^{-1}	90	98	95	86	82

ANOVA	df	$P > F$				
Cultivar	1	0.0301*	0.0440*	0.0272*	0.0352*	0.0828†
Fertilizer	2	0.6351	0.8321	0.8914	0.3594	0.4636
Cultivar x Fertilizer	2	0.7646	0.6987	0.7678	0.9263	0.4707
C.V. (%)		6.4	5.5	6.0	12.1	18.7

¶ Weeks after emergence.
‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-b] Mean values followed by the same letter (within columns) are not significantly different.
* Significant at $P < 0.05$.
† Significant at $P < 0.10$.

Table D.6. Soil water content of the 10-110 cm soil depth at the Rosebank-03 site.

Treatment: Cultivar	Treatment: Fertilizer	Emergence	3WAE¶	6WAE	9WAE	12WAE
		SWC (mm)				
45H21 (HY‡)	Control	382	423	369	296	287a
	160 kg N ha^{-1}: 0 kg S ha^{-1}	382	421	350	300	267ab
	160 kg N ha^{-1}: 27 kg S ha^{-1}	372	414	350	261	233b
Conquest (OP§)	Control	385	431	380	318	288a
	160 kg N ha^{-1}: 0 kg S ha^{-1}	397	427	379	321	291a
	160 kg N ha^{-1}: 27 kg S ha^{-1}	378	427	386	318	297a
Cultivar means						
45H21 (HY)		379	419	357b	286b	262b
Conquest (OP)		387	428	382a	319a	292a
	Fertilizer means					
	Control	383	427	375	307	287
	160 kg N ha^{-1}: 0 kg S ha^{-1}	389	424	365	311	279
	160 kg N ha^{-1}: 27 kg S ha^{-1}	375	421	368	290	265

ANOVA	df	P > F				
Cultivar	1	0.2888	0.2399	0.0344*	0.0213*	0.0571†
Fertilizer	2	0.2820	0.7955	0.5971	0.2098	0.3796
Cultivar x Fertilizer	2	0.6796	0.9256	0.4344	0.1476	0.0223*
C.V. (%)		3.3	4.8	5.1	5.6	5.6

¶ Weeks after emergence.

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

Table D.7. Net water loss between emergence and harvest at the Rosebank-03 site.

Treatment		Soil Depth					
Cultivar	Fertilizer	10-30 cm	30-50 cm	50-70 cm	70-90 cm	90-110 cm	10-110 cm
		NWL (mm)					
45H21 (HY‡)	Control	25	24	31	15c	0	95b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	28	27	32	22bc	6	115ab
	160 kg N ha^{-1}: 27 kg S ha^{-1}	27	24	35	43a	10	139a
Conquest (OP§)	Control	14	20	26	31ab	7	97b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	17	22	23	24bc	19	106ab
	160 kg N ha^{-1}: 27 kg S ha^{-1}	10	15	24	27bc	6	81b
Cultivar means							
45H21 (HY)		27a	25a	33	27	5	116
Conquest (OP)		13b	19b	24	27	11	95
	Fertilizer means						
	Control	19	22	28	23	3	96
	160 kg N ha^{-1}: 0 kg S ha^{-1}	23	25	27	23	13	110
	160 kg N ha^{-1}: 27 kg S ha^{-1}	18	19	29	35	8	110

ANOVA	df	$P > F$					
Cultivar	1	0.0417*	0.0637†	0.1005	0.9479	0.2151	0.1477
Fertilizer	2	0.7714	0.5119	0.8555	0.1213	0.2531	0.3566
Cultivar x Fertilizer	2	0.6327	0.8478	0.6683	0.0144*	0.3044	0.0318*
C.V. (%)		33.8	36.0	32.9	23.8	141.1	16.6

* Significant at $P < 0.05$.
‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-c] Mean values followed by the same letter (within columns) are not significantly different.
† Significant at $P < 0.10$.

Table D.8. Net water loss between emergence and 3WAE¶ at the Rosebank-03 site.

Treatment		Soil Depth					
Cultivar	Fertilizer	10-30 cm	30-50 cm	50-70 cm	70-90 cm	90-110 cm	10-110 cm
		NWL (mm)					
45H21 (HY‡)	Control	-5	-6	-12	-9	-8	-41
	160 kg N ha^{-1}: 0 kg S ha^{-1}	-4	-5	-13	-9	-7	-39
	160 kg N ha^{-1}: 27 kg S ha^{-1}	-2	-11	-14	-7	-7	-42
Conquest (OP§)	Control	-8	-9	-12	-8	-9	-46
	160 kg N ha^{-1}: 0 kg S ha^{-1}	1	-7	-10	-8	-7	-30
	160 kg N ha^{-1}: 27 kg S ha^{-1}	-5	-9	-14	-11	-10	-49
Cultivar means							
45H21 (HY)		-4	-7	-13	-8	-8	-41
Conquest (OP)		-4	-8	-12	-9	-9	-42
	Fertilizer means						
	Control	-7	-8	-12	-8	-8	-44
	160 kg N ha^{-1}: 0 kg S ha^{-1}	-2	-6	-11	-8	-7	-34
	160 kg N ha^{-1}: 27 kg S ha^{-1}	-4	-10	-14	-9	-9	-45

ANOVA	df	*P* > F					
Cultivar	1	0.9279	0.5146	0.4592	0.6601	0.5299	0.8358
Fertilizer	2	0.3994	0.1192	0.4700	0.9219	0.5230	0.2181
Cultivar x Fertilizer	2	0.4429	0.4061	0.6385	0.3101	0.6813	0.4382
C.V. (%)		-193.7	-32.6	-37.5	-47.1	-39.0	-39.8

¶ Weeks after emergence.
‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.

Table D.9. Net water loss between emergence and 6WAE¶ at the Rosebank-03 site.

Treatment		Soil Depth					
Cultivar	Fertilizer	10-30 cm	30-50 cm	50-70 cm	70-90 cm	90-110 cm	10-110 cm
		NWL (mm)					
45H21 (HY‡)	Control	3	7	10a	-1b	-6	13
	160 kg N ha^{-1}: 0 kg S ha^{-1}	8	20	8ab	0b	-4	32
	160 kg N ha^{-1}: 27 kg S ha^{-1}	6	5	8ab	6a	-4	22
Conquest (OP§)	Control	-1	3	5b	2ab	-4	5
	160 kg N ha^{-1}: 0 kg S ha^{-1}	9	4	5b	2ab	-3	17
	160 kg N ha^{-1}: 27 kg S ha^{-1}	-1	2	-1c	-2b	-6	-8
Cultivar means							
45H21 (HY)		6	11a	9a	1	-5	22a
Conquest (OP)		2	3b	3b	1	-4	5b
	Fertilizer means						
	Control	1b	5	7	0	-5	9b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	8a	12	7	1	-4	24a
	160 kg N ha^{-1}: 27 kg S ha^{-1}	3b	4	4	2	-5	7b

ANOVA	df	*P* > F					
Cultivar	1	0.1344	0.0410*	0.0098*	0.6147	0.8793	0.0548†
Fertilizer	2	0.0294*	0.1548	0.2006	0.6537	0.5591	0.0193*
Cultivar x Fertilizer	2	0.2408	0.2844	0.0818†	0.0205*	0.2955	0.1884
C.V. (%)		144.3	130.0	40.1	565.5	-69.2	98.4

¶ Weeks after emergence.

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

Table D.10. Net water loss between emergence and 9WAE¶ at the Rosebank-03 site.

Treatment		Soil Depth					
Cultivar	Fertilizer	10-30 cm	30-50 cm	50-70 cm	70-90 cm	90-110 cm	10-110 cm
		NWL (mm)					
45H21 (HY‡)	Control	21	23	28	17bc	-3	85b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	28	24	23	7c	0	82b
	160 kg N ha^{-1}: 27 kg S ha^{-1}	24	20	30	34a	2	111a
Conquest (OP§)	Control	9	16	19	23ab	1	67b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	15	21	20	15bc	4	75b
	160 kg N ha^{-1}: 27 kg S ha^{-1}	8	12	15	20b	6	61b
Cultivar means							
45H21 (HY)		24a	22a	27a	20	0	93a
Conquest (OP)		11b	16b	18b	19	4	68b
	Fertilizer means						
	Control	15	19	23	20ab	-1	76
	160 kg N ha^{-1}: 0 kg S ha^{-1}	21	23	22	11b	2	79
	160 kg N ha^{-1}: 27 kg S ha^{-1}	16	16	22	27a	4	86

ANOVA	df	$P > F$					
Cultivar	1	0.0312*	0.0238*	0.0326*	0.9030	0.1198	0.0067*
Fertilizer	2	0.4862	0.3504	0.8442	0.0455*	0.2366	0.6895
Cultivar x Fertilizer	2	0.8391	0.5927	0.1229	0.0767†	0.9997	0.0799†
C.V. (%)		38.2	31.9	29.3	41.5	449.9	23.3

¶ Weeks after emergence.

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

[a-c] Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

Table D.11. Net water loss between 3WAE¶ and 6WAE at the Rosebank-03 site.

Treatment		Soil Depth					
Cultivar	Fertilizer	10-30 cm	30-50 cm	50-70 cm	70-90 cm	90-110 cm	10-110 cm
		NWL (mm)					
45H21 (HY‡)	Control	8	14	22	7	2	54
	160 kg N ha^{-1}: 0 kg S ha^{-1}	12	26	21	9	3	71
	160 kg N ha^{-1}: 27 kg S ha^{-1}	9	16	22	13	4	64
Conquest (OP§)	Control	8	11	17	10	5	51
	160 kg N ha^{-1}: 0 kg S ha^{-1}	8	11	15	10	4	47
	160 kg N ha^{-1}: 27 kg S ha^{-1}	4	12	13	9	3	41
Cultivar means							
45H21 (HY)		10a	18a	22a	10	3	63a
Conquest (OP)		7b	11b	15b	10	4	46b
	Fertilizer means						
	Control	8	13	20	9	4	52
	160 kg N ha^{-1}: 0 kg S ha^{-1}	10	18	18	9	4	59
	160 kg N ha^{-1}: 27 kg S ha^{-1}	7	14	18	11	3	52

ANOVA	df	*P* > F					
Cultivar	1	0.0585†	0.0845†	0.0149*	0.8948	0.2534	0.0282*
Fertilizer	2	0.4497	0.4795	0.6076	0.5537	0.9911	0.4425
Cultivar x Fertilizer	2	0.5226	0.3913	0.5681	0.1664	0.1582	0.1759
C.V. (%)		45.0	63.3	27.4	38.7	38.4	21.8

¶ Weeks after emergence.
‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-b] Mean values followed by the same letter (within columns) are not significantly different.
* Significant at $P < 0.05$.
† Significant at $P < 0.10$.

Table D.12. Net water loss between 6WAE¶ and 9WAE at the Rosebank-03 site.

Treatment		Soil Depth					
Cultivar	Fertilizer	10-30 cm	30-50 cm	50-70 cm	70-90 cm	90-110 cm	10-110 cm
		NWL (mm)					
45H21 (HY‡)	Control	18	15ab	18	19	3	73
	160 kg N ha^{-1}: 0 kg S ha^{-1}	20	4b	15	7	4	50
	160 kg N ha^{-1}: 27 kg S ha^{-1}	17	15ab	22	28	6	89
Conquest (OP§)	Control	10	13ab	14	21	4	62
	160 kg N ha^{-1}: 0 kg S ha^{-1}	6	17a	15	12	7	58
	160 kg N ha^{-1}: 27 kg S ha^{-1}	9	9ab	16	22	13	69
Cultivar means							
45H21 (HY)		18a	11	18	18	4	71
Conquest (OP)		9b	13	15	18	8	63
	Fertilizer means						
	Control	14	14	16	20a	4	68
	160 kg N ha^{-1}: 0 kg S ha^{-1}	13	10	15	10b	6	54
	160 kg N ha^{-1}: 27 kg S ha^{-1}	13	12	19	25a	9	79

ANOVA	df	$P > F$					
Cultivar	1	0.0569†	0.5892	0.2441	0.9256	0.2669	0.4071
Fertilizer	2	0.9925	0.8125	0.1747	0.0540†	0.4000	0.1623
Cultivar x Fertilizer	2	0.7783	0.0763†	0.2935	0.4348	0.8280	0.4138
C.V. (%)		66.3	67.8	30.6	43.7	160.1	33.2

¶ Weeks after emergence.
‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-b] Mean values followed by the same letter (within columns) are not significantly different.
† Significant at $P < 0.10$.

Table D.13. Net water loss between 9WAE¶ and harvest at the Rosebank-03 site.

Treatment		Soil Depth					
Cultivar	Fertilizer	10-30 cm	30-50 cm	50-70 cm	70-90 cm	90-110 cm	10-110 cm
		NWL (mm)					
45H21 (HY‡)	Control	4	1	3	-2	3	10b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	1	3	8	15	6	33a
	160 kg N ha^{-1}: 27 kg S ha^{-1}	3	3	5	9	8	28ab
Conquest (OP§)	Control	4	4	6	8	6	30a
	160 kg N ha^{-1}: 0 kg S ha^{-1}	2	1	3	9	15	30ab
	160 kg N ha^{-1}: 27 kg S ha^{-1}	1	4	9	7	0	21ab
Cultivar means							
45H21 (HY)		3	3	5	7	6	24
Conquest (OP)		2	3	6	8	7	27
	Fertilizer means						
	Control	4a	3	5	3	5	20
	160 kg N ha^{-1}: 0 kg S ha^{-1}	1b	2	6	12	11	32
	160 kg N ha^{-1}: 27 kg S ha^{-1}	2ab	3	7	8	4	24

ANOVA	df	$P > F$					
Cultivar	1	0.8285	0.7266	0.7035	0.8233	0.6877	0.6501
Fertilizer	2	0.0671†	0.5077	0.6777	0.4089	0.3878	0.5588
Cultivar x Fertilizer	2	0.5069	0.1360	0.1424	0.2034	0.2515	0.0421*
C.V. (%)		114.8	87.1	117.9	122.9	155.1	33.0

¶ Weeks after emergence.
‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-b] Mean values followed by the same letter (within columns) are not significantly different.
* Significant at $P < 0.05$.
† Significant at $P < 0.10$.

Table D.14. Net water loss between 3WAE¶ and 9WAE at the Rosebank-03 site.

Treatment		Soil Depth					
Cultivar	Fertilizer	10-30 cm	30-50 cm	50-70 cm	70-90 cm	90-110 cm	10-110 cm
		NWL (mm)					
45H21 (HY‡)	Control	26	29	40	26	5	127
	160 kg N ha^{-1}: 0 kg S ha^{-1}	32	29	36	16	7	121
	160 kg N ha^{-1}: 27 kg S ha^{-1}	26	31	45	41	10	153
Conquest (OP§)	Control	17	24	31	31	9	113
	160 kg N ha^{-1}: 0 kg S ha^{-1}	14	28	30	22	11	106
	160 kg N ha^{-1}: 27 kg S ha^{-1}	14	21	28	31	16	110
Cultivar means							
45H21 (HY)		28a	30a	40a	28	7	133a
Conquest (OP)		15b	24b	30b	28	12	110b
	Fertilizer means						
	Control	22	27	36	28ab	7	120
	160 kg N ha^{-1}: 0 kg S ha^{-1}	23	29	33	19b	9	113
	160 kg N ha^{-1}: 27 kg S ha^{-1}	20	26	36	36a	13	131

ANOVA	df	P > F					
Cultivar	1	0.0223*	0.0374*	0.0885†	0.9674	0.1704	0.0369*
Fertilizer	2	0.9253	0.7016	0.5676	0.0339*	0.4378	0.3837
Cultivar x Fertilizer	2	0.7603	0.3482	0.3129	0.2858	0.9597	0.4538
C.V. (%)		53.6	20.4	22.8	26.7	103.8	23.5

¶ Weeks after emergence.

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

Table D.15. Net water loss between 3WAE¶ and harvest at the Rosebank-03 site.

Treatment		Soil Depth					
Cultivar	Fertilizer	10-30 cm	30-50 cm	50-70 cm	70-90 cm	90-110 cm	10-110 cm
		NWL (mm)					
45H21 (HY‡)	Control	30	31	43	24c	8	112c
	160 kg N ha^{-1}: 0 kg S ha^{-1}	32	33	45	31bc	13	136bc
	160 kg N ha^{-1}: 27 kg S ha^{-1}	29	34	50	50a	18	154ab
Conquest (OP§)	Control	22	28	38	39ab	16	181a
	160 kg N ha^{-1}: 0 kg S ha^{-1}	16	29	33	31bc	27	143bc
	160 kg N ha^{-1}: 27 kg S ha^{-1}	15	25	37	37abc	16	136bc
Cultivar means							
45H21 (HY)		31a	32a	46a	35	13	134
Conquest (OP)		18b	27b	36b	36	20	153
	Fertilizer means						
	Control	26	29	40	32	12	147
	160 kg N ha^{-1}: 0 kg S ha^{-1}	24	31	39	31	20	140
	160 kg N ha^{-1}: 27 kg S ha^{-1}	22	29	43	44	17	145

ANOVA	df	$P > F$					
Cultivar	1	0.0541†	0.0775†	0.0898†	0.8696	0.2524	0.2466
Fertilizer	2	0.8890	0.9248	0.6355	0.1600	0.3800	0.8921
Cultivar x Fertilizer	2	0.7561	0.4906	0.7159	0.0792†	0.4372	0.0306*
C.V. (%)		42.0	23.3	30.6	23.4	75.2	16.7

¶ Weeks after emergence.
‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-b] Mean values followed by the same letter (within columns) are not significantly different.
* Significant at $P < 0.05$.
† Significant at $P < 0.10$.

Table D.16. Canola seed yield, straw yield, evapotranspiration, grain and straw water use efficiencies (WUE) at the Rosebank-03 site.

Treatment						
Cultivar	Fertilizer	Evapotranspiration	Seed Yield	Straw Yield	WUEseed	WUEstraw
		---------mm---------	-------------kg ha^{-1}------------		----------kg ha^{-1} mm^{-1}---------	
45H21 (HY‡)	Control	305b	2438	4938	8.0	16.2
	160 kg N ha^{-1}: 0 kg S ha^{-1}	325ab	3695	7346	11.4	22.7
	160 kg N ha^{-1}: 27 kg S ha^{-1}	349a	4004	7914	11.4	22.7
Conquest (OP§)	Control	307b	1951	4675	6.6	15.6
	160 kg N ha^{-1}: 0 kg S ha^{-1}	316ab	1850	4889	5.9	15.6
	160 kg N ha^{-1}: 27 kg S ha^{-1}	291b	2367	5462	8.1	18.7
Cultivar means						
45H21 (HY)		326	3379a	6733a	10.3a	20.5
Conquest (OP)		304	2056b	5009b	6.8b	16.6
	Fertilizer means					
	Control	306	2195b	4807b	7.3b	15.9b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	320	2772ab	6118ab	8.7ab	19.1ab
	160 kg N ha^{-1}: 27 kg S ha^{-1}	320	3186a	6688a	9.8a	20.7a

ANOVA	df			$P > F$		
Cultivar	1	0.1477	0.0048*	0.0281*	0.0147*	0.1084
Fertilizer	2	0.3566	0.0258*	0.0315*	0.0825†	0.0943†
Cultivar x Fertilizer	2	0.0318*	0.1062	0.1764	0.1647	0.3105
C.V. (%)		5.5	22.5	23.5	24.6	24.0

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-b] Mean values followed by the same letter (within columns) are not significantly different.
* Significant at $P < 0.05$.
† Significant at $P < 0.10$.

8.5 APPENDIX E – ANALYSIS OF VARIANCE AND LEAST SQUARED MEANS FOR THE EFFECTS OF CULTIVAR AND FERTILIZER NITROGEN AND SULPHUR TREATMENTS ON SELECTED MEASUREMENTS ASSOCIATED WITH ROOTING HABIT OF CANOLA AT THE 2003 ROSEBANK EXPERIMENTAL SITE

Table E.1. Root count and biomass of the 0-10 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Root Count	Root Biomass	Root Biomass Count^{-1}
		--no. of root axes m^{-2}--	-----------g m^{-2}---------	--no. of root axes g^{-1}--
45H21 (HY‡)	Control	15944	n.d.	n.d.
	160 kg N ha^{-1}: 0 kg S ha^{-1}	14541	n.d.	n.d.
	160 kg N ha^{-1}: 27 kg S ha^{-1}	9184	n.d.	n.d.
Conquest (OP§)	Control	13138	n.d.	n.d.
	160 kg N ha^{-1}: 0 kg S ha^{-1}	16071	n.d.	n.d.
	160 kg N ha^{-1}: 27 kg S ha^{-1}	16964	n.d.	n.d.
Cultivar means				
45H21 (HY)		13223	n.d.	n.d.
Conquest (OP)		15391	n.d.	n.d.
	Fertilizer means			
	Control	14541	n.d.	n.d.
	160 kg N ha^{-1}: 0 kg S ha^{-1}	15306	n.d.	n.d.
	160 kg N ha^{-1}: 27 kg S ha^{-1}	13074	n.d.	n.d.
ANOVA	df		$P > F$	
		0.3902	n.d.	n.d.
		0.6595	n.d.	n.d.
		0.3327	n.d.	n.d.
		26.2	n.d.	n.d.

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
n.d. = data was not collected.

Table E.2. Root count and biomass of the 10-20 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Root Count	Root Biomass	Root Biomass Count^{-1}
		--no. of root axes m^{-2}--	-----------g m^{-2}---------	--no. of root axes g^{-1}--
45H21 (HY‡)	Control	5485	11.97	0.00238
	160 kg N ha^{-1}: 0 kg S ha^{-1}	8929	14.26	0.00241
	160 kg N ha^{-1}: 27 kg S ha^{-1}	6122	11.44	0.00216
Conquest (OP§)	Control	4337	19.97	0.00377
	160 kg N ha^{-1}: 0 kg S ha^{-1}	5230	17.62	0.00452
	160 kg N ha^{-1}: 27 kg S ha^{-1}	7270	12.32	0.00180
Cultivar means				
45H21 (HY)		6845	12.56	0.00336
Conquest (OP)		5612	16.64	0.00232
	Fertilizer means			
	Control	4911	15.97	0.00308
	160 kg N ha^{-1}: 0 kg S ha^{-1}	7079	15.94	0.00347
	160 kg N ha^{-1}: 27 kg S ha^{-1}	6696	11.88	0.00198

ANOVA	df		*P* > F	
Cultivar	1	0.3922	0.3073	0.2815
Fertilizer	2	0.5018	0.8023	0.3462
Cultivar x Fertilizer	2	0.5791	0.6079	0.4138
C.V. (%)		57.8	47.7	62.7

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

Table E.3. Root count and biomass of the 20-30 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Root Count	Root Biomass	Root Biomass Count^{-1}
		--no. of root axes m^{-2}--	----------g m^{-2}--------	--no. of root axes g^{-1}--
45H21 (HY‡)	Control	4337	3.18	0.00096
	160 kg N ha^{-1}: 0 kg S ha^{-1}	5995	7.63	0.00174
	160 kg N ha^{-1}: 27 kg S ha^{-1}	3954	7.38	0.00202
Conquest (OP§)	Control	5102	4.20	0.00080
	160 kg N ha^{-1}: 0 kg S ha^{-1}	5102	4.95	0.00114
	160 kg N ha^{-1}: 27 kg S ha^{-1}	3954	6.18	0.00155
Cultivar means				
45H21 (HY)		4889	6.06	0.00157
Conquest (OP)		4719	5.11	0.00117
	Fertilizer means			
	Control	4719	3.69	0.00088
	160 kg N ha^{-1}: 0 kg S ha^{-1}	5548	6.29	0.00144
	160 kg N ha^{-1}: 27 kg S ha^{-1}	4145	6.78	0.00178

ANOVA	df		$P > F$	
Cultivar	1	0.8461	0.4344	0.1758
Fertilizer	2	0.6000	0.1053	0.1029
Cultivar x Fertilizer	2	0.7798	0.4565	0.8070
C.V. (%)		47.2	62.8	51.8

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

Table E.4. Root count and biomass of the 30-40 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Root Count	Root Biomass	Root Biomass Count^{-1}
		--no. of root axes m^{-2}--	-----------g m^{-2}---------	--no. of root axes g^{-1}--
45H21 (HY‡)	Control	3571	3.53	0.00275
	160 kg N ha^{-1}: 0 kg S ha^{-1}	2679	5.02	0.00223
	160 kg N ha^{-1}: 27 kg S ha^{-1}	1913	5.42	0.00192
Conquest (OP§)	Control	3061	2.71	0.00091
	160 kg N ha^{-1}: 0 kg S ha^{-1}	3827	4.34	0.00118
	160 kg N ha^{-1}: 27 kg S ha^{-1}	3571	4.18	0.00115
Cultivar means				
45H21 (HY)		2721	4.65	0.00230
Conquest (OP)		3486	3.74	0.00108
	Fertilizer means			
	Control	3316	3.12	0.00183
	160 kg N ha^{-1}: 0 kg S ha^{-1}	3253	4.68	0.00170
	160 kg N ha^{-1}: 27 kg S ha^{-1}	2742	4.80	0.00154

ANOVA	df		$P > F$	
Cultivar	1	0.3373	0.4320	0.1109
Fertilizer	2	0.8339	0.4195	0.9462
Cultivar x Fertilizer	2	0.6426	0.9778	0.8216
C.V. (%)		77.9	89.8	126.0

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.

Table E.5. Root count and biomass of the 40-50 cm soil depth at the Rosebank-03 site.

Treatment		Root Count	Root Biomass	Root Biomass Count^{-1}
Cultivar	Fertilizer			
		--no. of root axes m^{-2}--	-----------g m^{-2}---------	--no. of root axes g^{-1}--
45H21 (HY‡)	Control	2806	4.31	0.00219
	160 kg N ha^{-1}: 0 kg S ha^{-1}	1531	4.99	0.00291
	160 kg N ha^{-1}: 27 kg S ha^{-1}	1148	3.01	0.00151
Conquest (OP§)	Control	2934	3.09	0.00117
	160 kg N ha^{-1}: 0 kg S ha^{-1}	3444	5.35	0.00155
	160 kg N ha^{-1}: 27 kg S ha^{-1}	2296	2.78	0.00133
Cultivar means				
45H21 (HY)		1828	4.11	0.00220
Conquest (OP)		2891	3.74	0.00135
	Fertilizer means			0.00169
	Control	2870	3.70	0.00223
	160 kg N ha^{-1}: 0 kg S ha^{-1}	2487	5.17	0.00142
	160 kg N ha^{-1}: 27 kg S ha^{-1}	1722	2.90	
ANOVA	df		$P > F$	
Cultivar	1	0.1687	0.7332	0.1373
Fertilizer	2	0.1576	0.2330	0.4788
Cultivar x Fertilizer	2	0.2147	0.8279	0.6715
C.V. (%)		36.4	87.6	96.9

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.

Table E.6. Root count and biomass of the 50-60 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Root Count	Root Biomass	Root Biomass Count^{-1}
		--no. of root axes m^{-2}--	-----------g m^{-2}---------	--no. of root axes g^{-1}--
45H21 (HY‡)	Control	1786	2.19	0.00125
	160 kg N ha^{-1}: 0 kg S ha^{-1}	1403	2.74	0.00246
	160 kg N ha^{-1}: 27 kg S ha^{-1}	893	2.60	0.00303
Conquest (OP§)	Control	2679	3.55	0.00169
	160 kg N ha^{-1}: 0 kg S ha^{-1}	2551	3.39	0.00118
	160 kg N ha^{-1}: 27 kg S ha^{-1}	893	2.74	0.00247
Cultivar means				
45H21 (HY)		1361	2.51	0.00224
Conquest (OP)		2041	3.23	0.00178
	Fertilizer means			
	Control	2232a	2.87	0.00147
	160 kg N ha^{-1}: 0 kg S ha^{-1}	1977a	3.06	0.00182
	160 kg N ha^{-1}: 27 kg S ha^{-1}	893b	2.67	0.00275

ANOVA	df		*P* > F	
Cultivar	1	0.3922	0.5274	0.4690
Fertilizer	2	0.0671†	0.9261	0.2606
Cultivar x Fertilizer	2	0.5580	0.8118	0.5500
C.V. (%)		82.5	64.3	82.9

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

† Significant at $P < 0.10$.

Table E.7. Root count and biomass of the 60-70 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Root Count	Root Biomass	Root Biomass Count^{-1}
		--no. of root axes m^{-2}--	-----------g m^{-2}---------	--no. of root axes g^{-1}--
45H21 (HY‡)	Control	1148	1.58	0.00143
	160 kg N ha^{-1}: 0 kg S ha^{-1}	893	3.21	0.00224
	160 kg N ha^{-1}: 27 kg S ha^{-1}	1148	1.65	0.00201
Conquest (OP§)	Control	2041	1.85	0.00130
	160 kg N ha^{-1}: 0 kg S ha^{-1}	1020	1.51	0.00218
	160 kg N ha^{-1}: 27 kg S ha^{-1}	1658	1.80	0.00083
Cultivar means				
45H21 (HY)		1063	2.15	0.00190
Conquest (OP)		1573	1.72	0.00144
	Fertilizer means			
	Control	1594	1.71	0.00137
	160 kg N ha^{-1}: 0 kg S ha^{-1}	957	2.36	0.00221
	160 kg N ha^{-1}: 27 kg S ha^{-1}	1403	1.73	0.00142
ANOVA	df		$P > F$	
Cultivar	1	0.4095	0.4261	0.3723
Fertilizer	2	0.4421	0.5400	0.3322
Cultivar x Fertilizer	2	0.7470	0.1360	0.6047
C.V. (%)		81.7	44.5	85.8

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

Table E.8. Root count and biomass of the 70-80 cm soil depth at the Rosebank-03 site.

Treatment: Cultivar	Treatment: Fertilizer	Root Count	Root Biomass	Root Biomass Count^{-1}
		--no. of root axes m^{-2}--	----------g m^{-2}---------	--no. of root axes g^{-1}--
45H21 (HY‡)	Control	765	2.06	0.00273
	160 kg N ha^{-1}: 0 kg S ha^{-1}	893	4.05	0.00639
	160 kg N ha^{-1}: 27 kg S ha^{-1}	383	1.13	0.00096
Conquest (OP§)	Control	1786	1.99	0.00152
	160 kg N ha^{-1}: 0 kg S ha^{-1}	510	1.88	0.00283
	160 kg N ha^{-1}: 27 kg S ha^{-1}	1020	1.30	0.00083
Cultivar means				
45H21 (HY)		680	2.41	0.00336
Conquest (OP)		1105	1.72	0.00173
	Fertilizer means			
	Control	1276	2.03	0.00213
	160 kg N ha^{-1}: 0 kg S ha^{-1}	702	2.96	0.00461
	160 kg N ha^{-1}: 27 kg S ha^{-1}	702	1.21	0.00089

ANOVA	df		*P* > F	
Cultivar	1	0.2915	0.5065	0.3781
Fertilizer	2	0.4029	0.2933	0.2576
Cultivar x Fertilizer	2	0.3401	0.4981	0.7340
C.V. (%)		115.7	109.3	174.4

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.

Table E.9. Root count and biomass of the 80-90 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Root Count	Root Biomass	Root Biomass Count^{-1}
		--no. of root axes m^{-2}--	-----------g m^{-2}---------	--no. of root axes g^{-1}--
45H21 (HY‡)	Control	638	1.30	0.00026
	160 kg N ha^{-1}: 0 kg S ha^{-1}	255	1.70	0.00211
	160 kg N ha^{-1}: 27 kg S ha^{-1}	128	6.87	0.00093
Conquest (OP§)	Control	1913	1.44	0.00077
	160 kg N ha^{-1}: 0 kg S ha^{-1}	1020	2.06	0.00283
	160 kg N ha^{-1}: 27 kg S ha^{-1}	383	1.20	0.00216
Cultivar means				
45H21 (HY)		340b	3.29	0.00110
Conquest (OP)		1105a	1.57	0.00192
	Fertilizer means			
	Control	1276a	1.37	0.00051
	160 kg N ha^{-1}: 0 kg S ha^{-1}	638b	1.89	0.00247
	160 kg N ha^{-1}: 27 kg S ha^{-1}	255b	4.03	0.00154

ANOVA	df		*P* > F	
Cultivar	1	0.0176*	0.2784	0.4805
Fertilizer	2	0.0334*	0.3592	0.2713
Cultivar x Fertilizer	2	0.3734	0.2278	0.9502
C.V. (%)		111.6	152.7	169.3

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-b] Mean values followed by the same letter (within columns) are not significantly different.
* Significant at $P < 0.05$.

Table E.10. Root count and biomass of the 90-100 cm soil depth at the Rosebank-03 site.

Treatment				
Cultivar	Fertilizer	Root Count	Root Biomass	Root Biomass Count^{-1}
		--no. of root axes m^{-2}--	-----------g m^{-2}---------	--no. of root axes g^{-1}--
45H21 (HY‡)	Control	0	1.08	n.d.
	160 kg N ha^{-1}: 0 kg S ha^{-1}	687	3.38	0.00623
	160 kg N ha^{-1}: 27 kg S ha^{-1}	333	1.63	0.00255
Conquest (OP§)	Control	706	2.25	0.00363
	160 kg N ha^{-1}: 0 kg S ha^{-1}	765	1.44	0.00190
	160 kg N ha^{-1}: 27 kg S ha^{-1}	128	0.88	0.00086
Cultivar means				
45H21 (HY)		340	2.03	0.00293
Conquest (OP)		533	1.52	0.00213
	Fertilizer means			
	Control	353	1.67	0.00181
	160 kg N ha^{-1}: 0 kg S ha^{-1}	726	2.41	0.00406
	160 kg N ha^{-1}: 27 kg S ha^{-1}	230	1.25	0.00171

ANOVA	df		*P* > F	
Cultivar	1	0.4131	0.5102	0.6450
Fertilizer	2	0.1244	0.4667	0.4879
Cultivar x Fertilizer	2	0.1713	0.2652	0.2018
C.V. (%)		123.5	138.3	219.6

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
n.d. = data was not collected.

8.6 APPENDIX F – ANALYSIS OF VARIANCE AND LEAST SQUARED MEANS FOR THE EFFECTS OF CULTIVAR AND FERTILIZER NITROGEN AND SULPHUR TREATMENTS ON SELECTED MEASUREMENTS ASSOCIATED WITH NITROGEN AND SULPHUR UPTAKE BY CANOLA AT THE 2003 ROSEBANK EXPERIMENTAL SITE

Table F.1. Midseason biomass, N and S concentrations and N and S accumulations of canola at the Rosebank-03 site.

Treatment						
Cultivar	Fertilizer	Biomass	N Concentration	S Concentration	N Accumulation	S Accumulation
		--kg ha^{-1}--	------------------%	------------------	------------------kg ha^{-1}	------------------
45H21 (HY‡)	Control	5878	2.6	0.72	152.1	42.6
	160 kg N ha^{-1}: 0 kg S ha^{-1}	6929	2.5	0.55	168.6	39.2
	160 kg N ha^{-1}: 27 kg S ha^{-1}	8273	2.6	0.56	209.9	46.4
Conquest (OP§)	Control	3758	3.5	0.94	127.5	33.9
	160 kg N ha^{-1}: 0 kg S ha^{-1}	4295	3.4	0.87	152.9	36.6
	160 kg N ha^{-1}: 27 kg S ha^{-1}	6761	3.7	0.79	254.5	54.5
Cultivar means						
45H21 (HY)		7027a	2.5b	0.61b	176.9	42.8
Conquest (OP)		4938b	3.5a	0.87a	178.3	41.6
	Fertilizer means					
	Control	4818b	3.0	0.83a	139.8b	38.3
	160 kg N ha^{-1}: 0 kg S ha^{-1}	5612b	2.9	0.71ab	160.7ab	37.9
	160 kg N ha^{-1}: 27 kg S ha^{-1}	7517a	3.1	0.68b	232.2a	50.4
ANOVA	df			$P > F$		
Cultivar	1	0.0008*	0.0049*	0.0002*	0.9513	0.8254
Fertilizer	2	0.0210*	0.8469	0.0846†	0.0597†	0.1447
Cultivar x Fertilizer	2	0.5738	0.8961	0.7684	0.4289	0.4085
C.V. (%)		18.8	23.8	19.8	35.7	30.1

‡ HY = Hybrid canola cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

Table F.2. Mature harvest biomass, N and S concentration and N and S accumulations of whole-plant canola at the Rosebank-03 site.

Treatment						
Cultivar	Fertilizer	Biomass	N Concentration	S Concentration	N Accumulation	S Accumulation
		---kg ha^{-1}---	---%---		---kg ha^{-1}---	
45H21 (HY‡)	Control	7376	1.5	0.60	108.0	44.8
	160 kg N ha^{-1}: 0 kg S ha^{-1}	11041	1.7	0.51	188.0	57.3
	160 kg N ha^{-1}: 27 kg S ha^{-1}	11918	1.8	0.50	217.1	59.0
Conquest (OP§)	Control	6626	1.7	0.66	113.4	43.8
	160 kg N ha^{-1}: 0 kg S ha^{-1}	6739	1.8	0.68	124.4	45.3
	160 kg N ha^{-1}: 27 kg S ha^{-1}	7830	2.0	0.74	156.2	56.6
Cultivar means						
45H21 (HY)		10112a	1.7	0.54b	171.0	53.7
Conquest (OP)		7065b	1.8	0.69a	131.3	48.6
	Fertilizer means					
	Control	7001	1.6	0.63	110.7b	44.3b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	8890	1.8	0.59	156.2ab	51.3ab
	160 kg N ha^{-1}: 27 kg S ha^{-1}	9874	1.9	0.62	186.6a	57.8a
ANOVA	df			*P* > F		
Cultivar	1	0.0138*	0.1623	0.0524†	0.1132	0.6396
Fertilizer	2	0.3051	0.1034	0.8101	0.0536†	0.0593†
Cultivar x Fertilizer	2	0.4250	0.7686	0.1878	0.1421	0.5105
C.V. (%)		23.0	10.9	14.0	21.7	23.4

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

Table F.3. Mature harvest yield, N and S concentration and N and S accumulations of canola seed at the Rosebank-03 site.

Treatment						
Cultivar	Fertilizer	Yield	N Concentration	S Concentration	N Accumulation	S Accumulation
		---kg ha^{-1}---	----%----		----kg ha^{-1}----	
45H21 (HY‡)	Control	2438	3.5	0.39	86.1	9.5
	160 kg N ha^{-1}: 0 kg S ha^{-1}	3695	4.0	0.42	144.7	15.4
	160 kg N ha^{-1}: 27 kg S ha^{-1}	4004	4.0	0.43	163.4	17.1
Conquest (OP§)	Control	1951	4.0	0.40	78.7	7.8
	160 kg N ha^{-1}: 0 kg S ha^{-1}	1850	4.2	0.43	78.1	8.2
	160 kg N ha^{-1}: 27 kg S ha^{-1}	2367	4.3	0.43	103.2	10.3
Cultivar means						
45H21 (HY)		3379a	3.8b	0.41	131.4a	14.0a
Conquest (OP)		2056b	4.2a	0.42	86.7b	8.8b
	Fertilizer means					
	Control	2195b	3.8	0.39	82.4b	8.6b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	2772a	4.1	0.43	111.4ab	11.8a
	160 kg N ha^{-1}: 27 kg S ha^{-1}	3186a	4.2	0.43	133.3a	13.7a

ANOVA	df			*P* > F		
Cultivar	1	0.0048*	0.0298*	0.5387	0.0335*	0.0108*
Fertilizer	2	0.0258*	0.2756	0.2237	0.0741†	0.0254*
Cultivar x Fertilizer	2	0.1062	0.6311	0.9559	0.1053	0.1745
C.V. (%)		22.5	7.8	6.6	22.9	23.9

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-b] Mean values followed by the same letter (within columns) are not significantly different.
* Significant at $P < 0.05$.
† Significant at $P < 0.10$.

Table F.4. Mature harvest yield, N and S concentration and N and S accumulations of canola straw at the Rosebank-03 site.

Treatment: Cultivar	Treatment: Fertilizer	Biomass	N Concentration	S Concentration	N Accumulation	S Accumulation
		---kg ha^{-1}---	---%---		---kg ha^{-1}---	
45H21 (HY‡)	Control	4938	0.45	0.71	21.8	35.3
	160 kg N ha^{-1}: 0 kg S ha^{-1}	7346	0.60	0.55	43.3	41.9
	160 kg N ha^{-1}: 27 kg S ha^{-1}	7914	0.68	0.53	53.7	41.9
Conquest (OP§)	Control	4675	0.73	0.77	34.7	36.1
	160 kg N ha^{-1}: 0 kg S ha^{-1}	4889	0.90	0.78	46.2	37.1
	160 kg N ha^{-1}: 27 kg S ha^{-1}	5462	0.98	0.86	53.0	46.3
Cultivar means						
45H21 (HY)		6733a	0.58b	0.60b	39.6	39.7
Conquest (OP)		5009b	0.87a	0.80a	44.6	39.8
	Fertilizer means					
	Control	4807b	0.59b	0.74	28.2b	35.7
	160 kg N ha^{-1}: 0 kg S ha^{-1}	6118a	0.75a	0.67	44.8a	39.5
	160 kg N ha^{-1}: 27 kg S ha^{-1}	6688a	0.83a	0.70	53.4a	44.1

ANOVA	df	$P > F$				
Cultivar	1	0.0281*	0.0980†	0.0656†	0.5488	0.9903
Fertilizer	2	0.0315*	0.0570†	0.6897	0.0357*	0.1613
Cultivar x Fertilizer	2	0.1764	0.9827	0.1606	0.5310	0.5431
C.V. (%)		23.5	21.4	17.3	27.1	23.9

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

Table F.5. Whole-plant N concentration of canola at the Rosebank-03 site.

Treatment: Cultivar	Treatment: Fertilizer	df	3WAE¶	6WAE	9WAE	12WAE
45H21 (HY‡)	Control		4.5	2.6	1.7	1.5
	160 kg N ha^{-1}: 0 kg S ha^{-1}		4.6	2.5	2.0	1.7
	160 kg N ha^{-1}: 27 kg S ha^{-1}		5.3	2.6	2.0	1.8
Conquest (OP§)	Control		4.9	3.5	1.9	1.7
	160 kg N ha^{-1}: 0 kg S ha^{-1}		5.4	3.4	2.5	1.8
	160 kg N ha^{-1}: 27 kg S ha^{-1}		5.0	3.7	2.4	2.0
Cultivar means						
45H21 (HY)			4.8	2.5b	1.9b	1.7
Conquest (OP)			5.1	3.5a	2.3a	1.8
	Fertilizer means					
	Control		4.7	3.0	1.8b	1.6
	160 kg N ha^{-1}: 0 kg S ha^{-1}		5.0	2.9	2.3a	1.8
	160 kg N ha^{-1}: 27 kg S ha^{-1}		5.1	3.1	2.2ab	1.9
ANOVA		**df**	**$P > F$**			
Cultivar		1	0.3223	0.0049*	0.0811†	0.1623
Fertilizer		2	0.5251	0.8469	0.0920†	0.1034
Cultivar x Fertilizer		2	0.4324	0.8961	0.5357	0.7686
C.V. (%)			19.9	23.8	13.6	10.9

¶ Weeks after emergence.

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

Table F.6. Whole-plant S concentration of canola at the Rosebank-03 site.

Treatment					
Cultivar	Fertilizer	3WAE¶	6WAE	9WAE	12WAE
45H21 (HY‡)	Control	0.82	0.72	0.59	0.60
	160 kg N ha^{-1}: 0 kg S ha^{-1}	0.57	0.55	0.53	0.51
	160 kg N ha^{-1}: 27 kg S ha^{-1}	0.59	0.56	0.51	0.50
Conquest (OP§)	Control	0.97	0.94	0.66	0.66
	160 kg N ha^{-1}: 0 kg S ha^{-1}	0.85	0.87	0.72	0.68
	160 kg N ha^{-1}: 27 kg S ha^{-1}	0.86	0.79	0.70	0.74
Cultivar means					
45H21 (HY)		0.66b	0.61b	0.54b	0.54b
Conquest (OP)		0.89a	0.87a	0.69a	0.69a
	Fertilizer means				
	Control	0.90a	0.83a	0.63	0.63
	160 kg N ha^{-1}: 0 kg S ha^{-1}	0.71b	0.71ab	0.62	0.59
	160 kg N ha^{-1}: 27 kg S ha^{-1}	0.73b	0.68b	0.60	0.62

ANOVA	df	P > F			
Cultivar	1	0.0071*	0.0002*	0.0666†	0.0524†
Fertilizer	2	0.0580†	0.0846†	0.8528	0.8101
Cultivar x Fertilizer	2	0.3969	0.7684	0.1793	0.1878
C.V. (%)		11.3	19.8	10.9	14.0

¶ Weeks after emergence.

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

a-b Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

8.7 APPENDIX G – ANALYSIS OF VARIANCE AND LEAST SQUARED MEANS FOR THE EFFECTS OF PREVIOUS CULTIVAR AND FERTILIZER NITROGEN AND SULPHUR TREATMENTS ON SELECTED MEASUREMENTS ASSOCIATED WITH NITROGEN AND SULPHUR UPTAKE BY UNFERTILIZED WHEAT FOLLOWING CANOLA AT THE 2004 ROSEBANK EXPERIMENTAL SITE

Table G.1. Midseason biomass, N and S concentration and N and S accumulations of wheat at the Rosebank-04 site.

Previous Treatment							
Cultivar	Fertilizer	Biomass	N Concentration	S Concentration	N Accumulation	S Accumulation
		---kg ha^{-1}---	---%---		---kg ha^{-1}---	
45H21 (HY‡)	Control	3978	2.0	0.13	77.8	5.2
	160 kg N ha^{-1}: 0 kg S ha^{-1}	4303	2.2	0.15	92.5	6.2
	160 kg N ha^{-1}: 27 kg S ha^{-1}	4319	2.1	0.14	89.2	5.9
Conquest (OP§)	Control	4775	1.9	0.13	88.8	6.0
	160 kg N ha^{-1}: 0 kg S ha^{-1}	4895	2.0	0.14	99.4	6.8
	160 kg N ha^{-1}: 27 kg S ha^{-1}	4434	2.0	0.14	91.0	6.1
Cultivar means						
45H21 (HY)		4200	2.1	0.14	86.5	5.7
Conquest (OP)		4701	2.0	0.13	93.0	6.3
	Fertilizer means					
	Control	4376	1.9	0.13	83.3	5.6
	160 kg N ha^{-1}: 0 kg S ha^{-1}	4599	2.1	0.14	95.9	6.5
	160 kg N ha^{-1}: 27 kg S ha^{-1}	4376	2.0	0.14	90.1	6.0

ANOVA	df			$P > F$		
Cultivar	1	0.2313	0.2633	0.4119	0.4825	0.3088
Fertilizer	2	0.8311	0.4732	0.4633	0.4870	0.5202
Cultivar x Fertilizer	2	0.6762	0.8040	0.5787	0.8977	0.9139
C.V. (%)		16.3	10.2	7.8	18.6	18.3

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

Table G.2. Mature harvest yield, N and S concentration and N and S accumulations of whole wheat plant at the Rosebank-04 site.

Previous Treatment: Cultivar	Previous Treatment: Fertilizer	Total Biomass	N Concentration	S Concentration	N Accumulation	S Accumulation
		----kg ha^{-1}----	----%	----%	----kg ha^{-1}----	----kg ha^{-1}----
45H21 (HY‡)	Control	6961	1.26	0.10	87.9	6.8
	160 kg N ha^{-1}: 0 kg S ha^{-1}	7706	1.26	0.10	97.3	8.0
	160 kg N ha^{-1}: 27 kg S ha^{-1}	7683	1.42	0.11	111.0	8.4
Conquest (OP§)	Control	8528	1.26	0.09	106.5	7.9
	160 kg N ha^{-1}: 0 kg S ha^{-1}	9250	1.38	0.11	129.1	10.4
	160 kg N ha^{-1}: 27 kg S ha^{-1}	9456	1.40	0.11	133.3	10.0
Cultivar means						
45H21 (HY)		7450b	1.32	0.10	98.7	7.7
Conquest (OP)		9078a	1.35	0.10	123.0	9.4
	Fertilizer means					
	Control	7744	1.26	0.10	97.2	7.3b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	8478	1.32	0.11	113.2	9.2a
	160 kg N ha^{-1}: 27 kg S ha^{-1}	8569	1.41	0.11	122.2	9.2a

ANOVA	df	$P > F$				
Cultivar	1	0.0592†	0.7456	0.9724	0.1304	0.1174
Fertilizer	2	0.4067	0.1175	0.1952	0.1286	0.0599†
Cultivar x Fertilizer	2	0.9815	0.4056	0.2218	0.8391	0.7140
C.V. (%)		16.4	7.5	6.4	23.8	17.3

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

† Significant at $P < 0.10$.

Table G.3. Mature harvest yield, N and S concentration and N and S accumulations of wheat seed at the Rosebank-04 site.

Previous Treatment							
Cultivar	Fertilizer	Yield	Protein	N Concentration	S Concentration	N Accumulation	S Accumulation
		--kg ha^{-1}--		--------%--------		--------kg ha^{-1}--------	
45H21 (HY‡)	Control	2762	13.8	2.4	0.14	66.9	3.8
	160 kg N ha^{-1}: 0 kg S ha^{-1}	2971	13.7	2.4	0.14	71.3	4.1
	160 kg N ha^{-1}: 27 kg S ha^{-1}	3057	14.8	2.6	0.15	80.4	4.5
Conquest (OP§)	Control	3349	13.1	2.3	0.13	76.3	4.2
	160 kg N ha^{-1}: 0 kg S ha^{-1}	3561	13.8	2.4	0.15	86.8	5.2
	160 kg N ha^{-1}: 27 kg S ha^{-1}	3492	14.5	2.6	0.14	89.3	4.9
Cultivar means							
45H21 (HY)		2930	14.1	2.5	0.14	72.9	4.1
Conquest (OP)		3467	13.8	2.4	0.14	84.1	4.8
	Fertilizer means						
	Control	3056	13.5b	2.4b	0.13	71.6	4.0
	160 kg N ha^{-1}: 0 kg S ha^{-1}	3266	13.8b	2.4b	0.14	79.1	4.6
	160 kg N ha^{-1}: 27 kg S ha^{-1}	3275	14.7a	2.6a	0.14	84.9	4.7

ANOVA	df	$P > F$					
Cultivar	1	0.1524	0.6470	0.6470	0.5067	0.2659	0.2633
Fertilizer	2	0.6549	0.0889†	0.0889†	0.2109	0.2450	0.2644
Cultivar x Fertilizer	2	0.9455	0.6141	0.6141	0.1409	0.8889	0.6275
C.V. (%)		17.9	5.9	5.9	6.7	21.7	20.3

‡ HY = Hybrid cultivar.
§ OP = Open-pollinated cultivar.
[a-b] Mean values followed by the same letter (within columns) are not significantly different.
† Significant at $P < 0.10$.

Table G.4. Mature harvest yield, N and S concentration and N and S accumulations of wheat straw at the Rosebank-04 site.

Previous Treatment						
Cultivar	Fertilizer	Straw Biomass	N Concentration	S Concentration	N Accumulation	S Accumulation
		----kg ha^{-1}----	--------------------%--------------------		-----------------kg ha^{-1}-----------------	
45H21 (HY‡)	Control	4199	0.50	0.07	21.0	2.9
	160 kg N ha^{-1}: 0 kg S ha^{-1}	4735	0.55	0.08	25.9	3.9
	160 kg N ha^{-1}: 27 kg S ha^{-1}	4626	0.65	0.09	30.6	3.9
Conquest (OP§)	Control	5179	0.60	0.07	30.2	3.7
	160 kg N ha^{-1}: 0 kg S ha^{-1}	5689	0.73	0.09	42.3	5.2
	160 kg N ha^{-1}: 27 kg S ha^{-1}	5964	0.73	0.09	44.0	5.1
Cultivar means						
45H21 (HY)		4520b	0.57	0.08	25.8b	3.6b
Conquest (OP)		5610a	0.68	0.08	38.8a	4.6a
	Fertilizer means					
	Control	4689	0.55	0.07	25.6b	3.3b
	160 kg N ha^{-1}: 0 kg S ha^{-1}	5212	0.64	0.09	34.1a	4.5a
	160 kg N ha^{-1}: 27 kg S ha^{-1}	5295	0.69	0.09	37.3a	4.5a

ANOVA	df			*P* > F		
Cultivar	1	0.0273*	0.2238	0.6806	0.0568†	0.0764†
Fertilizer	2	0.2781	0.1102	0.1750	0.0528†	0.0442*
Cultivar x Fertilizer	2	0.8609	0.5706	0.3608	0.7199	0.6930
C.V. (%)		15.8	15.0	6.0	30.9	14.5

‡ HY = Hybrid cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

Table G.5. N and S recovered by wheat crop at mature harvest following canola at the Rosebank-04 site.

Previous Treatment: Cultivar	Fertilizer	Soil NO_3^- concentration	Total plant N uptake	Recoverable N[y]	Soil SO_4^{2-} concentration	Total plant S uptake	Recoverable S[z]
		kg ha^{-1}					
45H21 (HY‡)	Control	11.2	87.9	99.1	92.4	6.8	99.2
	160 kg N ha^{-1}: 0 kg S ha^{-1}	18.5	97.3	115.8	69.4	8.0	77.4
	160 kg N ha^{-1}: 27 kg S ha^{-1}	16.8	111.0	127.8	60.5	8.4	68.9
Conquest (OP§)	Control	12.6	106.5	119.1	121.0	7.9	128.8
	160 kg N ha^{-1}: 0 kg S ha^{-1}	18.5	129.1	147.6	62.2	10.4	72.5
	160 kg N ha^{-1}: 27 kg S ha^{-1}	13.4	133.3	146.7	44.2	10.0	54.2
Cultivar means							
45H21 (HY)		15.5	98.7	114.2	74.1	7.7	81.8
Conquest (OP)		14.8	123.0	137.8	75.8	9.4	85.2
	Fertilizer means						
	Control	11.9	97.2	109.1	106.7	7.3b	114.0
	160 kg N ha^{-1}: 0 kg S ha^{-1}	18.5	113.2	131.7	65.8	9.2a	75.0
	160 kg N ha^{-1}: 27 kg S ha^{-1}	15.1	122.2	137.3	52.4	9.2a	61.5

ANOVA	df	$P > F$					
Cultivar	1	0.8485	0.1304	0.1757	0.9475	0.1174	0.8952
Fertilizer	2	0.3049	0.1286	0.1048	0.2171	0.0599†	0.2443
Cultivar x Fertilizer	2	0.8405	0.8391	0.8557	0.7470	0.7140	0.7575
C.V. (%)		62.5	23.8	22.2	93.2	17.3	85.0

‡ HY = Hybrid canola cultivar.

§ OP = Open-pollinated cultivar.

[a-b] Mean values followed by the same letter (within columns) are not significantly different.

† Significant at $P < 0.10$.

[y] Calculated as the sum of soil NO_3-N to 60 cm plus aboveground plant N accumulated at mature harvest.

[z] Calculated as the sum of soil SO_4^{2}-S to 60 cm plus aboveground plant S accumulated at mature harvest.