Determining the barriers to higher canola yields in Saskatchewan: an extensive analysis and a closer look at heat and water stress.

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Executive Summary

This study was initiated in response to a growing industry concerns that canola yields were declining or stagnating in the early to mid-nineties in Saskatchewan. Preliminary analyses of prairie yield data confirmed the presence of a yield stagnating trend or plateau. Further scrutiny of the yield data on a regional scale indicated that the yield decline may be confined to certain crop districts; in particular, crop districts 9A and 9B and to a lessor extent 5B depending on the years under study. It was felt that these regional differences in yield performance might form the basis for an investigation into which factors might be causing yield losses in certain regions of Saskatchewan.

A number of data sets containing historical crop production statistics were analyzed to look for possible associations between such factors and yield losses. Careful scrutiny of these data did not reveal any obvious correlations between production factors such as fertilizer rates or disease incidence and canola yield trends among the various crop districts. There was, however, a significant difference in overall fertilizer rates among provinces, particularly with respect to nitrogen and phosphate use where Manitoba rates for N and P were 50% greater than those in Saskatchewan.

Recognizing that weather can have a significant impact on crop yields, the canola yields and associated weather data were analyzed to look for possible associations which might explain the observed yield stagnation of the 90's. It was observed that precipitation and high temperature events, particularly during the month of July, correlated reasonably well with yields and it became apparent that a yield modeling effort designed to predict the response of canola to abiotic stresses of heat and water deficit might go a long way to address the yield decline issue.

In another attempt to understand yield decline, a one year field monitoring program was carried out to look at grower practices in a number of canola growing regions that might explain stagnating yields. This exercise did not show any clear relationships between production factors and yields.

Thus, a two-fold hypothesis was put forward: the yield problem was either due to abiotic stresses of heat and/or water deficit or due to insufficient fertilizer use. The fertilizer hypothesis would need to be tested in an extensive multiple variety and fertility field study beyond the resources of the present study. The abiotic stress hypothesis was deemed highly plausible and so a significant amount of effort was devoted to testing it by two methods: a replicated field trial and a crop modeling exercise.

The abiotic stress field study resulted in surprisingly minor effects of heat stress on yield components given the unusually hot and dry summer of 2001. The general trend was for heat stress during grain filling to have a larger impact on seed size and yield than stress during the flowering stage. Surprisingly, the stressed plants had more seeds per pod than the unstressed plants. In terms of grain quality, there was a tendency for the heat stressed plants to have higher protein and lower oil content although the effect was not significant. The unexpected high yields in the dryland plots may have resulted from lateral movement of water from the nearby irrigated plots, thus resulting in reduced heat stress effects. Nevertheless, while most of the heat stress effects were not statistically significant, they would still represent fairly significant economic losses to growers; e.g. the yield decrease of 13% caused by heat stress treatments would represent some $30/acre in a 40 bu/ac crop (@ $6.00/bu).

As part of the crop modeling exercise, a heat stress index termed the Stress Degree Day (SDD) analogous to the growing degree day (where SDD = Maximum daily temp - 25°C) was developed to obtain a quantitative relationship between yield and heat stress. It was determined that the cumulative SDD's in July was most strongly correlated with yields. In order to include the effects of water deficit into the model, a water use and phenology model developed by Environment Canada was use to determine the cumulative water stress at any point during the growing season. Having established that water deficit at crop maturity was most highly correlated with yields, both the heat stress index (JulySDD) and water deficit (WD) at maturity were combined in a single multiple regression equation. The number of years covered by the model was limited to the 1988 to 1999 period because of the unavailability of seeding dates prior to that period. To maintain independence between data used for model development and data used for yield prediction, the 4 year period from 1992-1995 was excluded from model development and became the focus of yield predictions based on weather conditions during that period. Actual yields which were not significantly different than predicted yields were deemed to have been affected exclusively by heat stress and water deficit. Conversely, yields which were less than those predicted by the model were presumed to have been affected by extraneous factors not included in the model. We found that 64% of the location years studied had yields which did not differ from predicted yields, implying that only heat stress and water deficit were responsible for yield loss. However, in some crop districts, most notably 1B and 5A and to a lessor extent 7B and 8A, the yields were significantly lower than predicted, suggesting that some other unknown factor was causing yield decline in those areas. While the limited disease survey data for that time period did not indicate any disease infestations in those areas, the above average rainfall in those areas during that period might have resulted in favorable conditions for disease incidence. Also, reports from the Western Committee on Crop Pests indicated that Bertha armyworm was a significant problem in 1994 in a region encompassing crop districts 1B and 5A, and that a diamondback moth infestation in 1995 was the worst in recent history.

In summary, it would appear that the growing conditions resulting in heat and water stress may have contributed significantly to the yield decline experienced in the 90's. There is no direct evidence to explain additional yield losses unaccounted for by these abiotic stresses, but insect pest survey reports for 1994-95 suggest that Bertha armyworm and diamondback moths may have contributed to this yield loss. Also, considering the relatively low fertilizer rates in Saskatchewan, it is probable that insufficient fertilizer application played a role in the lower overall yields in Saskatchewan.

1. Introduction

The present study was initiated in response to a growing concern expressed by Saskatchewan canola growers regarding a problem of decreasing or stagnating yields (Button, 1996). A survey carried out after the 1995 and 1996 crop seasons (Brandt, 1996; Panchuk, 1996) to address this problem failed to pinpoint the likely cause of the yield decline. The growers identified a list of possible factors (Table 1) ranging from climatic conditions to disease and insect pests and soil fertility, with the highest probability attributed to conditions of high temperature (heat stress) during the critical periods of flowering and early seed set. This was reflected in a common concern expressed by growers that, in many cases, their crops looked very promising with good uniform stands and adequate pod formation, but often yielded only half of expected yields with many shrunken and shriveled seeds and many pods with undeveloped seeds (Button, 1996). This study was initiated to confirm the existence of a canola yield decline problem in Saskatchewan and to determine what was causing this problem.

At the outset, this study was guided by the following principles:

a) The very existence of a yield decline problem was not to be taken for granted but had to be supported by actual and accurate yield data.

b) While field monitoring activities and anecdotal information from growers could be used to develop a hypothesis concerning the cause of the yield decline, only actual data archived or published by reliable sources, such as government surveys, scientific field surveys, weather archives, etc., as well as from replicated field trials, could be used to support or refute any hypothesis put forward.

c) The investigation could be allowed to digress from its original path in response to new evidence and unexpected findings.

With these guiding principles, the basic approach for this investigation was to proceed in the following manner: a) confirm the existence of a yield decline problem, b) formulate a hypothesis through extensive analysis of crop production data and field monitoring activities, c) test the hypothesis using yield modeling techniques and replicated trials, and d) summarize results and draw conclusions.

2. Canola Yield Decline: Fact or Fiction.

The first order of business in this investigation was to ascertain the existence of a yield decline problem in Saskatchewan and if it existed, to determine its relative significance on a local and prairie-wide scale. Given the inherent variability of crop yields from year to year or from decade to decade, it was important to realize how yield trends can be shown to vary significantly, depending on the length of the period being considered. For example, if we focus on the canola yield trend over the 12-year period from 1988 to 1999 (Fig. 1a), there was a fairly healthy trend of increasing yields (gaining approximately 5 bu/ac over that period) and conclude that the canola yield issue is a non-issue. However, 1988 was the worst drought year the prairies have ever experienced, thereby skewing the 1988-99 yield trend in a very positive way. An examination of average canola yields dating back to the 70's and even earlier during the rapeseed years, revealed a different picture of how canola is performing in the 90's (Fig. 1b). From a pre-canola (rapeseed) yield level of approximately 18 bu/ac, the bar was raised considerably with the advent of canola to greater than 23 bu/ac (excluding the dry year of 1979). After the 1988 drought, yields recovered but not quite to pre-drought levels (the record yield of 27 bu/ac in 1999 was due to exceptional growing conditions). With improved production technologies and superior varieties, it could be argued that canola yields in the 90's should have averaged closer to 25 bu/ac; instead they were 10% lower at 22.6 bu/ac.

Another useful approach in assessing the yield performance of canola over the past few decades is to compare it with yield trends of other major crops in Saskatchewan. This revealed that by the end of the 90's, crops like flax and barley were still increasing with time whereas canola appeared to have peaked in the early 90's (Fig. 2a). It was also useful to compare the yields over the past 4 decades with those of Alberta and Manitoba (Fig. 2b). It is apparent from these comparisons that canola yields in Saskatchewan were doing well relative to the other provinces until the 90's when average yields were 7% and 16% less than in Alberta and Manitoba, respectively.

In general, there appears to be enough evidence from historical yield data to indicate that canola yields in Saskatchewan have stagnated during the 90's and therefore a thorough investigation to uncover the reasons for the unrealized yield potential is warranted.

3. Formulating a hypothesis.

3.1. Introduction.

The biggest challenge in developing one or more hypotheses to explain this yield decline problem was to obtain reliable long-term production data relating to the many factors affecting canola crop yields. Because our preliminary data analysis appeared to indicate that the onset of the yield problem was not necessarily a sudden event but rather a gradual process which likely occurred over the last decade or so, it was recognized that access to historical production statistics on agronomic inputs, cultural practices, pest infestation levels, etc. spanning the last 2 decades would be invaluable to the task at hand.

Unfortunately, such long-term data sets do not exist except for historical yield and weather records. There have been some recent efforts in conducting disease and weed surveys in the past 5 years, most notably a prairie-wide disease survey carried out from 1996 to 1998 (Morrall, 1999), but these do not span the entire period of interest for the present investigation and are often limited in the number of sites surveyed due to budget and time constraints. One useful source of information on agronomic practices has been the Management Plus Program (Morrow, 2001) implemented by the Saskatchewan Crop Insurance Corporation beginning in 1996. It is a voluntary program whereby farmers who obtain coverage from SCIC agree to provide valuable information regarding their farming practices, including dates of operations, crop varieties seeded, fertilizer rates, etc. From its modest beginnings in 1996 when only about 400 canola fields were reported, the program has grown to over 5,000 fields reported in the year 2000, providing good representation from all of the crop districts in the province.

Despite the limited time span of the data sets, which precluded any valid extrapolations to pre-1996 crop years, they did serve a very useful purpose in making comparisons between crop districts within Saskatchewan as well as between provinces. Such comparisons, when associated with corresponding yield data, were valuable in assessing the role of various factors in the yield decline issue, and provided valuable input in formulating a working hypothesis. The analysis of historical yield and weather data, for which there exits a reliable and complete record dating back to the beginnings of canola production, was considered crucial in formulating a hypothesis. Since weather is arguably the most important factor affecting crop growth and yield, it was deemed paramount that this information be scrutinized extensively to determine if it might hold the answer to the yield decline problem. Lastly, it was decided early on in the investigation that a field monitoring program might be a useful exercise in order to take a close look at present farming practices in the hopes of finding some clues as to how specific farming practices might be associated with declining canola yields.

3.2. Canola production analysis.

3.2.1. Preamble.

As a preamble to this preliminary analysis, it was necessary to adopt a basic premise allowing us to use relatively short-term (3-5 years) data to make inferences on a yield trend spanning a longer time period. The premise was essentially the following: if the data doesn't allow us to observe changes in crop production factors and associated yield changes over a long (~ 2 decades) time period, then we can look at differences in canola yields among the various growing regions or crop districts to see whether such differences might be correlated with differences in management practices or growing conditions within these crop districts. Assuming that the relative differences in production factors observed among the crop districts were fairly constant throughout the 90's, (e.g. crop district 9A fertilizer rates were usually 15% more than crop district 5A, etc.), then it may be useful to compare these relative factor levels with the associated yield trends to infer a cause/effect relationship. It turns out, in fact, that there are significant differences in yield trends among the various crop districts. In order to provide sufficient averaging to smooth out year-to-year variations, and considering that the yield decline or "plateau" phenomenon appeared to be confined to the 90's, the yield trend parameter selected for analysis was the % change from the 80's to the 90's; i.e. the % change in mean yields from the 80's to the 90's.

Figure 3 shows these yield trends in the principal canola growing crop districts of Saskatchewan. It is immediately obvious that the yield decline problem is not a general one but appears to be confined to certain areas of the province such as the North-Central/North-West

(C.D. 9A & 9B) and a couple of other districts (5B and 7B). On the other hand, certain regions like the South-East (C.D.'s 1 & 2) have experienced significant yield increases. The challenge now is to explain why there is such a difference in yield trends among certain crop districts and which factors might be responsible for these differences. In light of this premise, we will proceed to examine crop production data from various sources.

3.2.2. Management Plus Program (MPP).

Fertilizer use data from the MPP were available for the 1998 to 2000 crop years (no fertilizer use data prior to 1998) and are presented in figures 4a to 4d. If we compare crop districts 9a & 9B (greatest yield decline, see fig. 3) with crop districts 1A & 1B (greatest yield increase), there is very little difference in fertilizer rates which would account for such a difference in yield trend. In fact, crop districts 9A & 9B showed greater potassium and sulphur use than C.D.'s 1A & 1B. Overall fertilizer use increased slightly over the 3-year period for N, K & S but declined slightly for P fertilizer.

In order to gain additional insight into the soil fertility factor, an extensive soil test data set was obtained from a commercial soil testing facility (Enviro-Test Labs, Inc.) comprised of the entire archive of soil tests carried out from 1995 to 2001 and averaged by year and crop district. It was hoped that an examination of pre-season soil levels of N, P, K, and S might provide some indication of possible nutrient deficiencies in certain crop districts which could explain corresponding yield differences. As is evident from figures 5a to 5d, soil N was as good in crop districts 9A and 9B as in crop district 1A and soil P was actually greater in 9A & 9B. While the levels of K and S appeared to be significantly lower in C.D.'s 9A & 9B, it is apparent from figures 4c and 4d that growers were well aware of such deficiencies and responded with much greater rates of K and S fertilizer.

With Manitoba running a similar MPP program, it was possible to obtain some of their fertilizer use data up to the 1997 crop year and compare them to the Saskatchewan rates to get a sense of the different fertilizer practices in both provinces (Fig. 6a). It is quite revealing to see a very large difference in nitrogen rates with Manitoba rates nearly 30 lbs/ac (50%) greater than

Saskatchewan rates. Phosphorous use was also greater by 10 lbs/ac (50%) in Manitoba, whereas P and K were similar. Fertilizer rates obtained from the 1997-98 Canola Disease Survey (Morrall, 1999) also showed similar differences in fertilizer use (Fig. 6b) although this data source would be considered less accurate due to the much smaller number of fields sampled.

While the crop district comparisons did not suggest any relationship between fertilizer rates and yield trends in the 90's, the comparison with Manitoba rates is worthy of careful consideration and may prove to be the strongest argument in favor of a link between fertilizer practices and declining canola yields. There is evidence that the capacity of soils to supply nutrients is declining steadily due to cropping practices that deplete nutrient reserves over time. This point will be revisited later after having considered all other factors.

3.2.3. Canola Disease Survey (1996-98).

A common theory put forward to explain the canola yield decline issue has been the possibility that the dramatic increase in canola production over the last 2 decades has resulted in a shortening of the crop rotations, thereby increasing the incidence of diseases with subsequent yield losses. It is very difficult to substantiate this theory with hard data as there hasn't been a concerted effort to systematically survey the canola growing areas of Saskatchewan over the last decade or more. One of the most comprehensive efforts in assessing canola disease incidence throughout the prairies was the Canola Disease Survey (Morrall, 1999) carried out from 1996 to 1998. While the period is too short to show any trends, it is useful to look at crop district comparisons as was done with the fertilizer data to see if there are any disease/yield associations.

In general, there did not appear to be any obvious differences in disease incidence among crop districts that would explain the differences in yield trends, except for the blackleg lesion infection level which appeared to be higher in crop districts 9A & 9B (Figs. 7a to 7c). Given that the total number of fields surveyed each year was only in the range of 100 to 120, it is likely that such differences would not be statistically significant. Some useful indicators of disease pressure, namely the # of years since the last canola crop and the # of years since the last sclerotinia-susceptible crop, were examined to see how they varied among crop districts (Figs. 8a and 8b) .

There did not appear to be any significant differences among crop districts, with the indicators averaging approximately 4 and 3 years between canola crops and sclerotinia-susceptible crops, respectively. A four year rotation between canola crops is recommended to avoid disease problems in canola.

In order to obtain an estimated long-term trend in this disease pressure indicator, one can calculate from production data a % of seeded acreage in canola. A value averaging 25% would theoretically suggest a 1 in 4 year rotation, a 33% average would suggest a 1 in 3 rotation, etc.. By running the analysis from 1980 to 1997, it was observed that most crop districts were at or below the 25% safety threshold throughout most of the period under study (Fig. 9). However, this type of analysis doesn't take into consideration the number of growers who do not grow canola and therefore these canola acreage percentages could be underestimated.

In brief, there was not enough evidence to indicate that increased disease incidence was responsible for declining canola yields in Saskatchewan. The lack of a comprehensive long-term disease survey program makes it difficult to make conclusive statements one way or another.

3.2.4. Weather Data Analysis.

3.2.4.1. Introduction

It is well recognized that weather is the most important factor affecting crop yields, especially with a crop like canola which is known to be quite sensitive to moisture deficits and excessive heat at critical stages of development. Consequently, it was important to study the weather records over the past few decades to determine whether the canola yield decline was caused by unfavorable growing conditions. To this end, it was important to show the relationship between weather factors and yields and then to demonstrate how a change in weather conditions could have resulted in the observed yield decline.

3.2.4.2. Precipitation.

The precipitation records of weather stations in the main canola growing regions of Saskatchewan (all crop districts except 3 & 4) and the corresponding yield records from surrounding rural municipalities were examined carefully to look for similarities in precipitation and yield trends. Despite the inherent spatial variability of precipitation and the difficulty in relating a point source record to a yield record representing an entire municipality, it was possible to observe an interesting yield/precipitation relationship among crop districts. Figure 10 represents the precipitation and yield trends, expressed as % changes from the 80's to the 90's, for a number of weather stations located in canola growing regions of Saskatchewan. It is interesting to note that crop districts 9A and 9B, which experienced the greatest yield decline, also had corresponding decreases in summer precipitation over the same period. On the other hand, crop districts 8A and 8B, which experienced a positive yield trend, had corresponding positive trends in precipitation. As is evident from figure 10 and from many other observed yield/precipitation relationships not presented here, the correlation between yield and summer precipitation is not always positive, suggesting that this "bulk" summer precipitation variable may need to be refined enough to take into account the timeliness of the rain events relative to certain critical stages of crop development. This is demonstrated by figure 11 which represents precipitation trends during May, June and July (Fig. 11a) and corresponding yield trends (Fig. 11b) for selected R.M.'s in crop district 9B. The important thing to note here is that the 2 municipalities that experienced a yield increase (R.M.'s 470 & 499) were the only 2 that had corresponding increases in July precipitation. This is consistent with the fact that water deficits in July, which is a critical period for flowering and seed set, can have significant effects on canola yields. The fact that a more specific precipitation variable (July as opposed to growing season precipitation) was more closely related with yields exemplifies the need to employ crop modeling techniques for predicting canola response to weather conditions. If one could develop a good yield model based on crop response to water deficits and heat stress, for example, then it may be possible to determine whether the yield decline problem was simply due to adverse weather conditions or whether other unknown factors were involved. This work will be presented in a later section. Suffice it to say at this point that, based on the yield/precipitation relationships observed so far, the hypothesis that moisture deficit was involved in the yield decline problem would be an important one to consider.

3.2.4.3. Heat Stress.

While the yield limiting effects of moisture deficits are well known, it is also accepted that excessive heat, particularly during the critical stages of flowering and early seed set, can cause significant decreases in yield. This adverse effect of heat can be seen in figures 12a and 12b which display yields and mean July maximum temperatures over the past 25 years at two locations in Saskatchewan. The yield and temperature trends tend to be mirror images of each other, reflecting the negative relationship between yield and heat. As with precipitation, one could certainly refine the heat stress variable to one that represents the adverse effect of cumulative heat exposure at one or more critical stages of development. For example, we might utilize a Stress Degree Day (SDD) concept analogous to the Growing Degree Day, whereby the accumulation of temperature above a certain "heat stress" threshold temperature would be used to quantify the degree of heat exposure. This work will also be presented in a later section.

3.2.5. Field Monitoring Program.

Having scrutinized a number of canola production and weather data sets, it was felt that a field monitoring program, encompassing a large portion of the Parkland region where most of the canola is grown, might provide some additional clues as to how grower practices were affecting yields. Monitoring sites were established during the 1999 field season in four canola fields in each of five crop districts in the Parkland region (total of 20 fields), representing areas with varying canola yield trends as discussed previously (Fig. 3). Each field site was monitored for precipitation, soil moisture, crop biomass accumulation rates, crop inputs, disease incidence and grain yield. The field sites were within 10 km of a standard Environment Canada weather station.

Growing conditions during the summer were quite favorable to canola production, with cooler temperatures (mean July maximum temperatures 2-4 °C less than normal) and greater precipitation (up to 50% greater than normal in some regions). This produced average yields of 32 bu/ac (5 bu/ac greater than the record provincial average of 27 bu/ac) which apparently confounded most relationships of yield with production factors. Soil moisture contents were generally greater than 20% (vol.) throughout June and July when moisture stress can have a large impact on yields. This resulted in no apparent relationship between yields and soil moisture content (Fig. 13a). These optimal growing conditions resulted in a wide range of crop stands, as reflected in crop biomass measurements, but this did not correlate well with final yields (Fig. 13 b). This suggests that a high yielding potential as reflected by a heavy crop stand does not necessarily translate into higher yields, emphasizing the need for more research in the area of assimilate partitioning and translocation as it relates to grain filling.

The wide range of N, P K and S fertilizer rates did not correlate at all with total accumulated biomass (data not shown) nor with final grain yields (Fig. 14). This lack of response was surprising in view of the fact that the excellent growing conditions would have been expected to promote increased growth and yields from higher inputs. Similarly, the degree of disease incidence did not correlate well with crop yields (Fig. 15), suggesting that disease levels were below economic threshold levels.

In summary, the field monitoring program did not provide any additional information with which to support any hypotheses put forward to explain the yield decline problem. The exercise basically provided a "snapshot" of commercial canola production over a single growing season which happened to be characterized by optimum growing conditions. It was subsequently decided that the field monitoring approach was not the appropriate technique for explaining a long-term yield trend and was therefore discontinued after the first year.

3.2.6. A working hypothesis.

After careful consideration of all the information gathered and generated, the most compelling evidence points to two possible causes for declining canola yields: one being abiotic stress from both heat and water deficit, and the other being insufficient fertilizer application. As this fertilizer hypothesis would require testing within an extensive field program beyond the scope and resources of this project, the focus was directed towards the abiotic stress hypothesis, with the objective of testing this hypothesis through crop modeling techniques and a replicated field trial.

The rationale for this approach was as follows: if we were successful in predicting crop yield response to abiotic stress, then any yield decline unaccounted for by the abiotic stress model would likely be due to another factor, possibly the suspected fertilizer factor. If, on the other hand, the predicted yields based on abiotic stress modeling were similar to the observed yields, then this would suggest that abiotic stresses played the major role in yield decline and that fertilizer use was not a significant factor. In studying the abiotic stress hypothesis, it was felt that a replicated field trial to determine the response of canola to heat and drought stress would be of great value to this program and provide scientific evidence for the abiotic stress hypothesis. The remainder of this report will focus on activities designed to support or refute this working hypothesis.

4. Testing our hypothesis.

4.1. Heat and drought stress field study.

4.1.1. Rationale

The objective of this study was to develop and implement a field technique for assessing the effect of heat and drought stress on canola growth and yield. The challenge was to maintain control plots at predetermined "unstressed" canopy temperatures in order to compare them to heat stressed plots exposed to ambient conditions. By applying the heat stress treatments at different growth stages, we were hoping to demonstrate how the response varies depending on the critical periods when the stress was imposed. This would allow us to estimate the yield loss due to excessive heat over a number of years in Saskatchewan by using historical yield and weather data.

4.1.2. Methodology.

In order to maintain an experimentally sound protocol involving small plot replication, a technique was developed to randomly apply canopy temperature treatments to individual plots in a RCBD experimental design. The treatments were obtained by allowing plots to be exposed to either ambient (stress) conditions or by cooling the plot canopies to a non-stressed threshold temperature. This was accomplished by an evaporative cooling system whereby individual plots received short (30 sec) pulses of sprinkled water, delivered by low-volume micro-sprinklers, when the canopy temperature measured by infrared thermometry reached a threshold temperature of 25 °C. The system was automatically controlled by a portable weather station and was linked by a cellular system to an office PC, thereby allowing remote desktop monitoring and data downloading. The weather station was equipped with standard weather sensors for continuous monitoring of heat stress conditions, including air and canopy temperatures, humidity, wind speed, solar and net radiation.

A total of four heat stress treatments were imposed:

1) Full Stress (FS) - plots exposed to ambient conditions all season long.

2) Early Stress (ES) - plots exposed to ambient conditions during the flowering period.

3) Late Stress (LS) - plots exposed to ambient conditions during the grain filling period.

4) No Stress (NS) - plots maintained at or below the threshold temperature throughout the season.

In order study direct soil moisture effects as well as interactive effects of soil moisture and heat stress on yields, the study was carried out side by side on dryland and irrigated land. The soil moisture contents under both regimes were monitored weekly using a TRACE TDR instrument (Soil Moisture Corp., Santa Barbara, CA).

A schematic diagram of the experimental layout is provided in figure 16. The site was located at the Canada-Saskatchewan Irrigation and Diversification Centre (CSIDC) at Outlook, SK where a combination of light textured soils, relatively dry and hot climate and a good irrigation supply system made it an ideal location for this type of study. Because of technical difficulties with the IR thermometers during the 2000 season, the canopy treatments were not imposed for a long enough period to produce any treatment effects. The system performed remarkably well during the 2001 season which turned out to be an ideal season for heat stress work due to the unusually hot and dry conditions during that summer. The results presented here will be exclusively from the 2001 season.

4.1.3. Experimental results.

4.1.3.1. System performance.

Figure 17 presents a typical diurnal pattern of crop canopy temperatures and atmospheric conditions obtained on August 13, 2001, showing how well the cooled canopies of the ES and NS treatments were being maintained at the 25°C threshold temperature (LS treatment not measured at this time). On this particular day, the fact that the FS canopy temperature was 4-5 °C greater than the air temperature would suggest a severely stressed crop. In terms of quantifying the degree of heat stress experienced by the FS treatment relative to the ES and NS treatments, one could consider the area between the FS and the 25 °C line (ES and NS lines) to represent the amount of heat stress experienced by the FS treatment. By summing up these daily quantities of heat over the specific periods of interest (e.g. flowering period), it was possible to quantify the cumulative heat stress experienced by the various treatments. In the interest of adapting a measure of heat exposure which could also be used in the analysis of temperature/yield relationships using historical weather and production data, a Stress Degree Day (SDD) concept alluded to earlier was employed. The SDD is defined as a cumulative heat stress parameter and expressed as follows: $SDD_{jk} = \sum (Tmax_i - 25)$ where $Tmax_i$ is the maximum temperature of day i and 25 is a base temperature considered to be the point above which canola becomes heat stressed, and j and k are the first and last day over which the stress is accumulated. Over the course of the experiment, the following heat stress conditions occurred:

Period	Dates	SDD's
Early Stress	July 4 - July 18	52.1
Late Stress	July 19 - Aug 15	84.1
Full Stress	July 4 - Aug 15	136.2

Thus the plots in the early stress treatment were exposed to 52.1 SDD's from July 4 to July 18 after which they were maintained below 25°C by cooling and did not accumulate SDD's after July 18, and so forth. With the summer of 2001 being unusually hot and dry, it was felt that these stressful conditions would have a significant effect on growth and yield components in canola, in particular in the dryland plots which received no irrigation after May 15.

4.1.3.2. Treatment effects.

Much to our surprise, we did not find any significant effect of heat stress or soil moisture on grain yield or crop biomass (Fig. 18). There was a tendency for the yields in the full stress and late stress treatments (both having the grain filling period in common) to have lower yields in both irrigated and dryland plots but this was not statistically significant. There was also a tendency for the crop biomass in the early stress treatment to be slightly greater than the other treatments but again this was not significant. With regards to effects on yield components, the stress treatments did not affect the number of pods per plant (Fig. 19a) but there appeared to be some effect on the number of seeds per pod, with the full stressed dryland plots having more seeds per pod than the unstressed plants (Fig. 19b). As well, the average seed weight did not appear to differ among treatments (Fig. 20a), although the distribution of seed size was affected in that there was a greater proportion of small seeds in the FS and LS than in the ES treatments under dryland (Fig. 20b). A similar trend was seen in the irrigated plots but not at a significant level. The effect of heat stress on grain quality was not significant although there was a tendency for the protein content to increase and the oil content to decrease when the grain filling period (FS and LS treatments) was being stressed (Fig. 21).

The relatively small effects of heat stress and soil moisture were quite surprising given the extreme conditions of drought and heat experienced during the 2001 growing season. In particular, the average yield of the dryland plots (47 bu/ac) was only 7% less than that of the irrigated plots, compared to a province-wide average of 19 bu/ac which represents a 30% decrease relative to 1999 record levels of 27 bu/ac. While our soil moisture measurements did indicate lower soil moisture in the dryland plots during the early stress period, there was a significant amount of precipitation in the first 2 weeks of the late stress period which may have been sufficient to mitigate any negative effects of heat stress on the grain yield and yield components. Furthermore, it is possible that there may have been a significant amount of residual moisture in the deeper soil profile owing to the previous year's crop of irrigated potatoes as well as possible sub-surface lateral movement of water from the irrigated portion of the trial. In general, our results indicated a tendency for the grain filling period to be more sensitive to heat stress than the flowering period, not only in terms of grain quantity but also of grain quality. The tendency of protein content to increase and oil content to decrease is consistent with observed effects of drought. Our results indicated a stronger effect of heat stress than of soil moisture.

4.1.4. Conclusions

While most of the heat stress effects were not statistically significant, they would represent fairly significant economic losses to growers. In particular, the yield decrease from heat stress occurring during the grain filling period was on the order of 13% which, in a 40 bu/ac crop, would represent over $30/acre (@ $6.00/bu canola). It may be necessary to repeat this experiment with a more stringent sampling protocol to reduce variability so as to confirm the significance of the heat stress effects. As well, deeper soil moisture monitoring would provide more information regarding the influence of soil moisture in mitigating the effects of heat stress.

4.2. Crop Modeling

4.2.1. Heat Stress

As discussed earlier, there appears to be some good correlations between historic canola yields and corresponding indicators of heat stress (see Fig. 12). It is particularly interesting to look at the relationship between canola yields and the climatic conditions during the month of July which coincides with most of the flowering period as well as a portion of the grain filling period. If we use an index of heat, such as the Stress Degree Day (SDD) concept presented earlier, and plot yields against SDD's using data for a number of years in a particular location, we usually find a linear and negative relationship (Fig. 22a). A linear regression analysis usually yields a regression equation which explains anywhere from 40% to 70% of the variability in the yields. By regressing yields against SDD's for a number of years and locations representing the canola growing crop districts, we could then estimate yields based on the regression equations using historical weather data. By comparing observed yields with predicted yields based on the regression equations, we could determine whether the changes in yield from year to year were due to climatic conditions or whether some other factors were involved. That is, if predicted yields were close to actual yields, then heat stress alone was the determinant factor affecting yields. Conversely, any large discrepancies between observed and predicted yields would suggest the importance of some other factors. Figure 22b shows an example of observed and predicted yields for the Wynyard area in crop district 6A.

4.2.2. Water deficit.

Recognizing the importance of precipitation and moisture availability to crop growth and yield, it was believed that the addition of a water deficit factor to the heat stress model would improve its predictive capability and therefore improve our ability to explain the observed yield variations. A water use and phenology model developed by the Atmospheric Sciences Division of Environment Canada (Ash et al, 1992; Raddatz et al., 1994 and 1996) was used for this purpose. This model is used operationally by Manitoba Agriculture to provide weekly updates of soil moisture conditions and projected maturity dates for a number of crops including canola. The required inputs for the model include daily minimum and maximum temperatures and precipitation as well as site specific data such as available water holding capacity of the soil and seeding dates.

Since records for seeding dates were only available for the period from 1988 to 1999, the combined heat stress and water deficit model was limited to that particular period. Nevertheless, it was felt that this period of years would suffice to address the yield decline issue which appeared to originate in the early 90's. The model was run from 1988 to 1999 for approximately 40 locations throughout Saskatchewan, starting with an assumed soil moisture of 50% of available water holding capacity in 1988 (a reasonable estimate due to the dry conditions of 1988). As the model progresses through a particular growing season, it calculates among other parameters daily water deficits (difference between the available supply from the soil and the demand from evapotranspiration) and accumulates this deficit for any specified period. Preliminary analyses, where correlations between yields and water deficits at various stages were compared, indicated that the cumulative water deficit at maturity was the one most highly correlated with yields. The water deficit at maturity was therefore used as the water stress factor in our combined heat and water stress model. The combined model simply involved a multiple linear regression of yields against JulySDD's and water deficit (WD) for the years 1988 to 1999. Figure 23 shows a comparison of actual and modeled yields using either a simple heat stress model or a combined heat stress and water deficit model for the Wynyard and North Battleford areas.

In order to validly predict yields using a model, it is important that the model be developed using independent data outside of the period of interest. Since the available data was from a relatively short span of 12 years and given that a 4-year period from 1992-95 was showing a general decline in yield in most crop districts (Fig. 24), it was decided that the regression model would be developed using only data outside this 92-95 period so that valid yield predictions for that period could be done. As this period was immediately preceding the 1995-96 surveys in which growers had expressed their concerns of declining yields, this 4-year period would have been the one most present in their minds regarding the yield decline problem. Table 2 presents the coefficients and R^2 values of the separate multiple regression equations for the 14 locations and corresponding crop districts. It is apparent that there is quite a range in the coefficients and R^2 values for the different locations.

In order to obtain a single representative relationship between yield and abiotic stress, the decision was made to develop a single multiple regression equation for all locations rather than retain the separate regressions described above. While this approach might reduce the overall accuracy of yield predictions for individual crop districts, it was felt that it was the most sensible approach as it might allow us to determine in a more consistent manner the true portion of yield loss due to abiotic stress at each location. That is, assuming that heat and water stress affect canola yields equally regardless of crop district, then a single model would attribute a consistent amount of yield loss to these abiotic stresses so that any remaining discrepancy between actual and predicted yields could be attributed to some other possibly common extraneous factor. Comparing the magnitude of such discrepancies with other production factors among each of the crop districts might provide a clue as to which other factor is contributing to yield loss. If, on the other hand, we find little discrepancy between actual and predicted yields, then we would conclude that the model contains the principal factors affecting yields (heat and water deficit) and that there were no other extraneous factors involved.

Using yield data from 14 locations representing the main canola growing regions in Saskatchewan, a single multiple regression equation was obtained as follows:
Yield (bu/ac) = -0.116 x JulySDD's - 0.017 x WD + 27.7 ($R^2 = 0.66$) where JulySDD is the cumulative Stress Degree Days for July (base 25°C) and WD is the cumulative water deficit (mm) at maturity as determined by the Environment Canada water use and phenology model. The intercept value of 27.7 can be interpreted as the maximum yield under no heat stress and water deficit conditions, with average management in use in the province. Interestingly, this value corresponds to the record breaking average canola yields in Saskatchewan in 1999 when growing conditions were considered optimum.

Using this relationship, the actual and modeled yields and associated standard errors were plotted over the 1988 to 1999 period for each location and the 4-yr periods from 1992 to 1995 were examined to determine if there were significant differences between actual and modeled yields (Figs. 25 to 31). The modeled yields outside of the 4-year period of interest have been plotted for the sake of continuity and perspective but should not be accorded undue significance because of the fact that they are not independent of the data used to develop the model.

4.2.3. Results and discussion.

In order to determine whether factors other than heat and drought caused lower than expected yields during the 92-95 period, we looked at how many of the actual yields in the 56 location years (14 locations x 4 years) fell within the standard error of the corresponding modeled yields. Actual yields falling within the standard error of the modeled yields were taken as not being significantly different from the modeled yields, implying that the factors of heat and water deficit in the model were exclusively responsible for yield variations. Conversely, actual yields falling outside the standard errors of modeled yields were deemed to have been affected by additional factors extraneous to the model.

By doing this, we found that 36 (64%) of the yields fell within the standard error of the predicted yields, suggesting that a significant portion of the yields during this period were accounted for by conditions of heat stress and water deficit as defined by the regression model (Table 3a). This left 17 (36%) of the yields which were significantly lower than the predicted yields, and this shortfall in yield was presumably due to some other extraneous factors not included in the model. Crop districts 1B and 5A were particularly conspicuous in that yields were significantly lower than expected (modeled) in all 4 years. Figure 32a shows that the average yields in those crop districts were well below the overall average for that period (figure 32b, which represents average canola yields in the entire crop districts, is included here to emphasize the fact that the yield data used in our modeling work (obtained from means of municipalities surrounding the weather stations) do not necessarily represent the entire crop districts. It is, nevertheless, more valid to use these averaged municipal yields and associated weather data for the modeling exercise). Crop districts 5B, 7B and 8A each had 2 to 3 years with significantly lower than expected yields and figure 32a shows that yields in those 3 crop districts were slightly lower than average.

The large discrepancy between actual and modeled yields in crop districts 1B and 5A suggests that some additional factor(s) other than heat and water deficit may have been responsible for the yield losses. One factor which often comes to mind as a prime suspect in causing yield loss is diseases, particularly sclerotinia and blackleg. Unfortunately, there is little reliable disease survey data covering the location years of interest and so there is no hard evidence to support this hypothesis. It may be possible to speculate on the potential for disease infestation in those regions during that particular time period based on climatic conditions. If we look at the precipitation record associated with crop districts 1B and 5A, we find that in 3 of the 4 years the total summer precipitation (May to August) was between 15% and 30 % greater than the 25-yr normal (Table 2b). Such conditions would be conducive to sclerotinia development which may have contributed to reducing yields below expected levels during this period.

Another possible cause of the lower yields in that region might be insect damage. According to reports from the Western Committee on Crop Pests (Western Committee on Crop Pests, 1992-1995), the favorable growing conditions in 1992 reduced the amount of insect damage, but in 1994 the Bertha armyworm was a significant problem in the region along the Saskatchewan-Manitoba border between Pelly and the U.S. border, an area which includes the problematic C.D.'s 1B and 5A. Producers were apparently unprepared for the infestation and considerable damage was sustained before they could spray. In 1995, the diamondback moth infestation was the largest in recent memory and the larvae caused substantial damage to crops in the bud and early flower stage. They exceeded the previously accepted economic threshold of 200-300 per square meter. Bertha armyworm was also a significant problem with 0.4 M hectares sprayed. The dense crop canopy made control measures very difficult.

Thus there is evidence to suggest that the additional shortfall in canola yields during the 1992 to 1995 period may have been caused by disease and insect pests. The lack of recorded disease data to substantiate this claim points to the importance and need for more extensive and methodical disease surveys in the province so as to identify problem areas and improve our understanding of disease/yield relationships.

5. General discussion and conclusions.

This investigation into the causes of unrealized canola yields in Saskatchewan involved a systematic approach, beginning with the analysis of available data on grower practices and agronomic surveys and progressing towards a more detailed study of the effects of abiotic stresses on canola yields. At the outset, the underlying premise in this study was that the yield decline problem had been identified by farmers concerned with unexpected low yields over a number of years and therefore the answer was to be found in some production factor that had somehow attained a level that was limiting yields. In other words, it wasn't by field experimentation alone that a solution to the problem would be found. Rather, it was felt that a careful examination of historical production factors such as diseases, fertilizer practices, etc. over the period encompassing the advent of the yield problem would be effective in demonstrating the cause and effect relationship leading to lower yields. Unfortunately, such long-term production statistics do not exist and it was necessary to extrapolate information from relatively recent (5 years) data sets. This was done by comparing long-term yield trends among crop districts with corresponding short-term trends in production factors. These efforts did not provide any concrete evidence to demonstrate the contribution of certain agronomic factors to the yield decline problem.

The lure to devote a considerable amount of effort into the study of weather factors such as temperature and precipitation was not solely due to the recognition of these factors as being crucial to crop growth and yield, but was also due to the fact that the available data was essentially complete throughout the entire history of canola production itself. With so many years of weather and yield data at our disposal, it was possible to determine with a reasonable degree of accuracy the relationship between canola yield and the yield-limiting factors of heat and water stress (using the modeling approach) and therefore to assess how much of the perceived yield decline problem was due to these abiotic stresses. It was therefore possible to see that in many cases, the yield decreases observed were in large part due to weather conditions. There was circumstantial evidence, from records of favorable weather conditions and survey reports, that the remaining decreases could be due to disease and insect pest damage, respectively. It is also possible that the relatively low fertilizer rates, especially N and P, in Saskatchewan may be a factor in the yield decline problem due to cropping practices which may be depleting soil nutrient reserves over time. There needs to be a continuous research effort to confirm or refute this possibility.

The modeled maximum yield of 27.7 bu/ac is considerably lower than yields exceeding 60 bu/ac that have been documented on a field scale in Saskatchewan. This suggests that considerable yield improvement can be achieved with better management and cultivar selection when conditions are favorable. The challenge lies in developing and transferring the decision making tools that growers need to take economic advantage of this potential.

There is no doubt that the modeling process used in this study could be subject to errors due, for example, to the limitation of assigning the weather conditions from one station to an entire rural municipality or more. By using a larger number of years and locations, and hopefully by increasing the density of weather reporting stations across Saskatchewan, it would be possible to improve the accuracy of the model and thus provide a better understanding of canola yield and weather relationships. We will also need to continue to collect more agronomic information such as the Canola Disease Survey by Saskatchewan Agriculture and Food or the Management Plus Program of Saskatchewan Crop Insurance Corporation in order to develop a reliable data base of information to help us understand how present and future crop species and cultivars are responding to environmental conditions and grower cultural practices.

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b)Sources of data:

Alberta:

Crop Production Statistics: Albert Shaw and Don Hansen, Alberta Agriculture, Food and Rural Development.

Websites:

Precipitation data: http://www.agric.gov.ab.ca/navigation/sustain/climate/index.html

Production data: http://www.agric.gov.ab.ca/economic/stats/stats_fldcrop.html

Saskatchewan:

Production stats: Dale Sikora, Saskatchewan Agriculture and Food, Regina, SK

Jeff Morrow, Management Plus Program, Data Analyst. Saskatchewan Crop Insurance Corporation, Melville, Saskatchewan.

Weather data: Terry Karwandy, Saskatchewan Agriculture and Food, Regina, SK.

Disease data: Penny Pearse, Saskatchwan Agriculture and Food, Regina, SK

Robin Morrall, Saskatoon, SK. Coordinator of prairie-wide 1996-98 Canola Disease Survey.

Soil fertility data: Pat Flaten and Troy McInnis, Enviro-Test Labs, Inc., Saskatoon, SK

Web Sites:

Yields by R.M. http://www.agr.gov.sk.ca/apps/rm-yields/default.asp

Crop Reports: http://www.agr.gov.sk.ca/Reports.asp

Manitoba:

Production Data: Carol Gunvaldsen, Crops Industry Analyst, Manitoba Agriculture and Food.

Normand Mabon, Management Plus Program, Manitoba Agriculture and Food, Somerset, MB.

Web Sites:

Management Plus Program: http://www.mmpp.com/index.html

Figure 1a

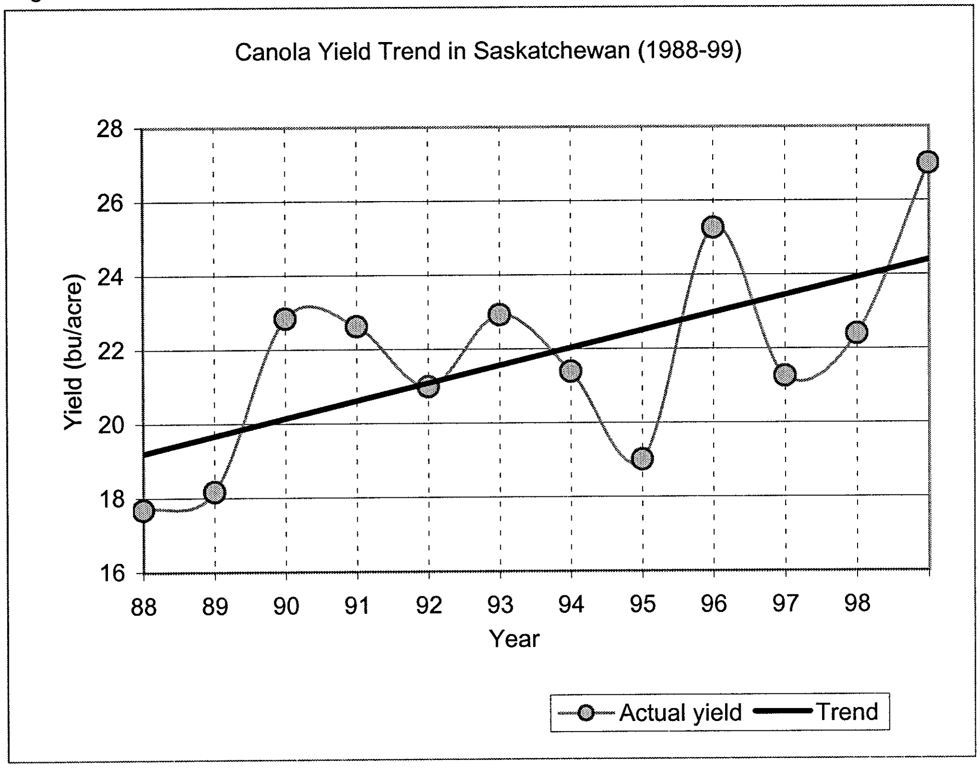


Figure 1b

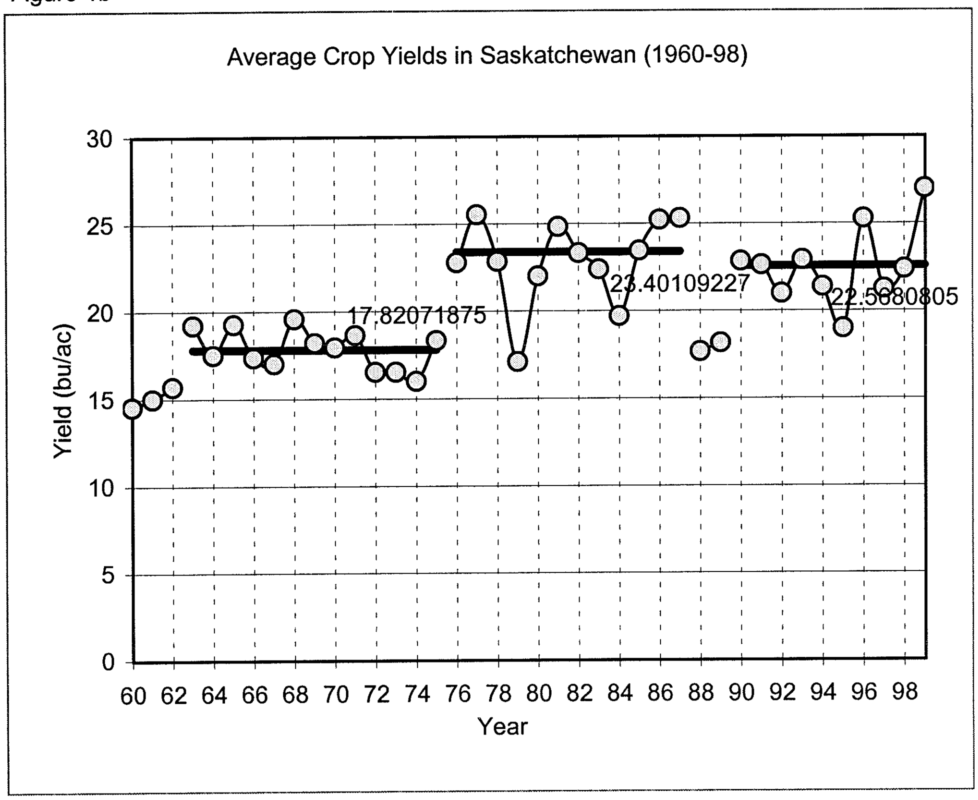


Figure 2a

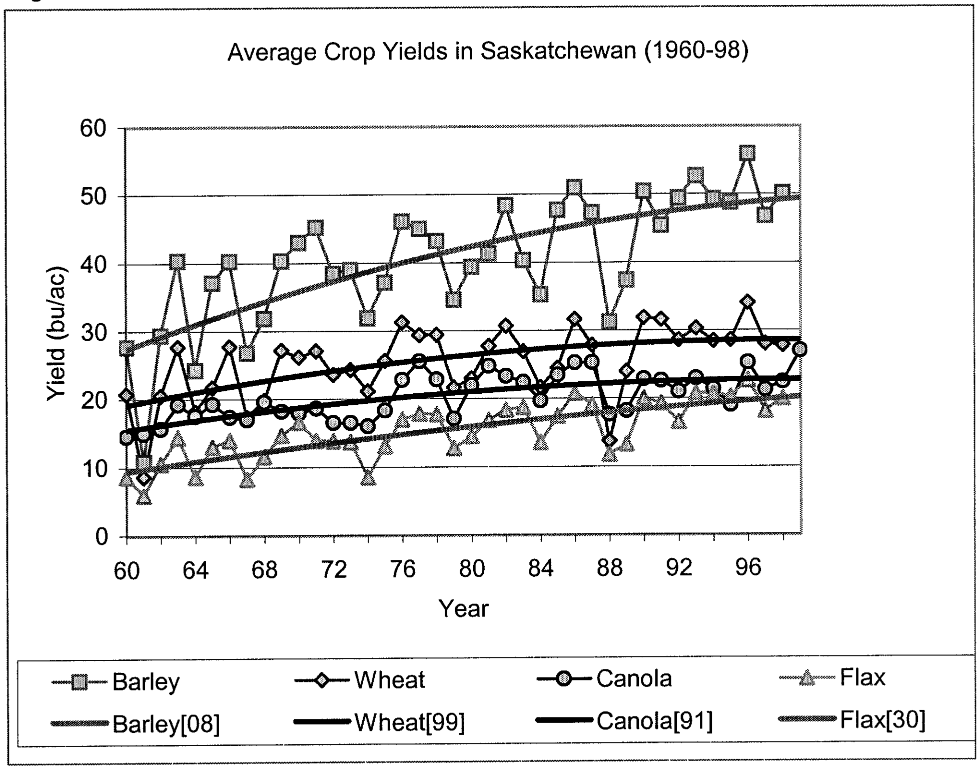


Figure 2b

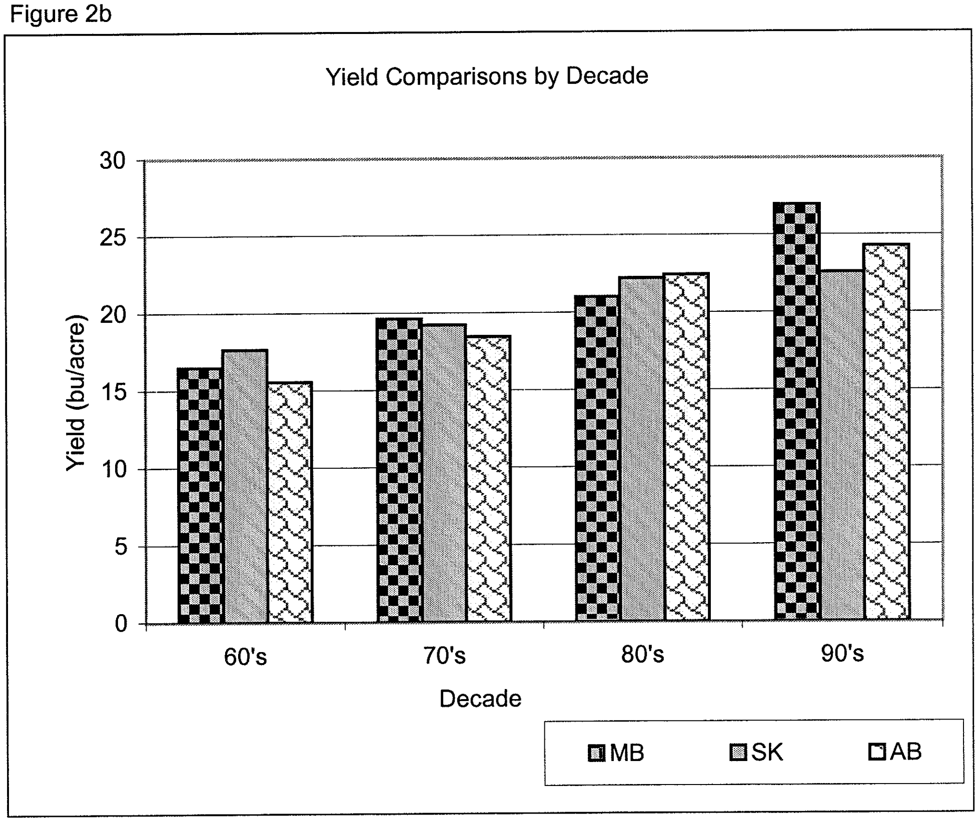


Figure 3. Change in average yields from the 1980's to the 1990's.

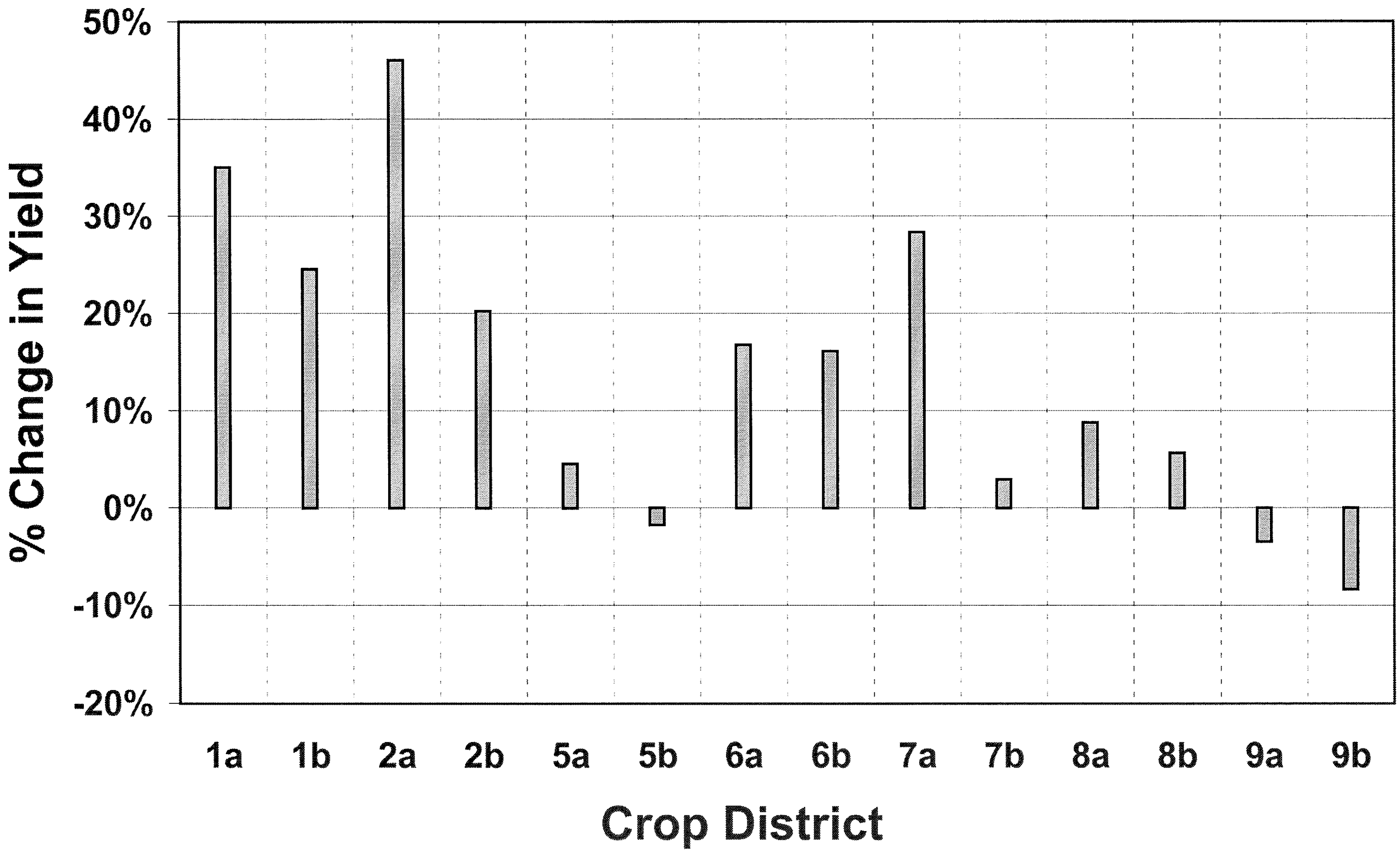


Fig. 4a Nitrogen Fertilizer Use by Crop District 1998-2000
Overall Averages: 1998: 50.5 1999: 57.1 2000: 58.0

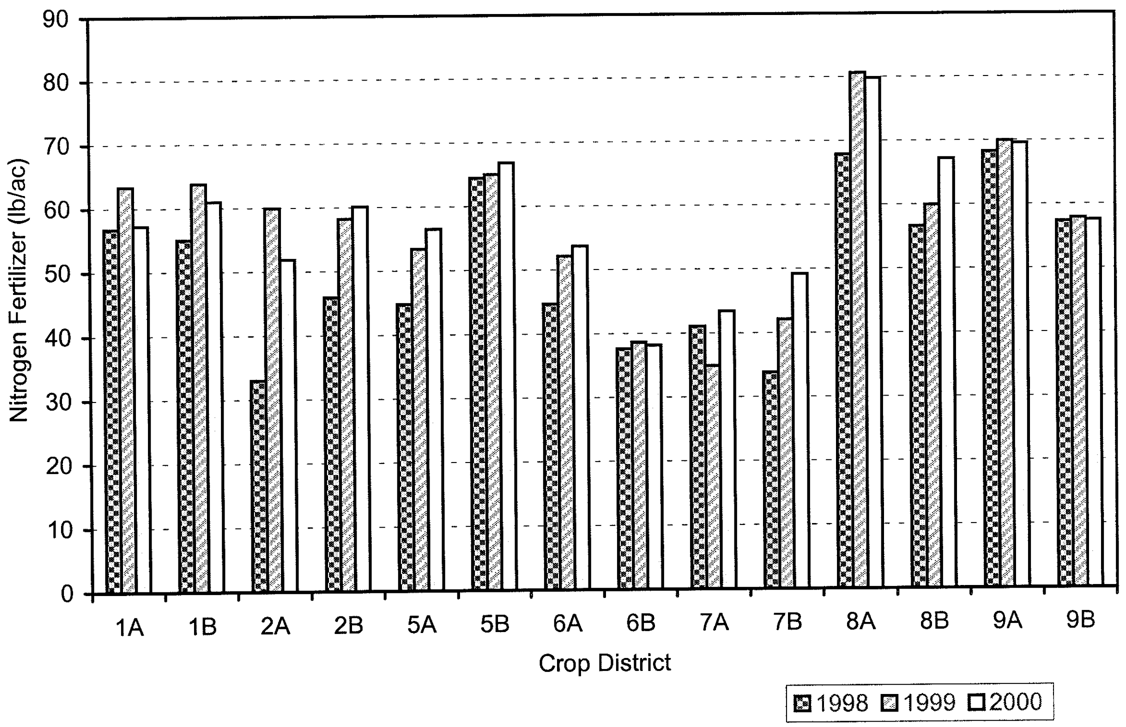


Fig. 4b Phosphate Fertilizer Use by Crop District 1998-2000
Overall Averages: 1998: 21.9 1999: 21.7 2000: 21.3

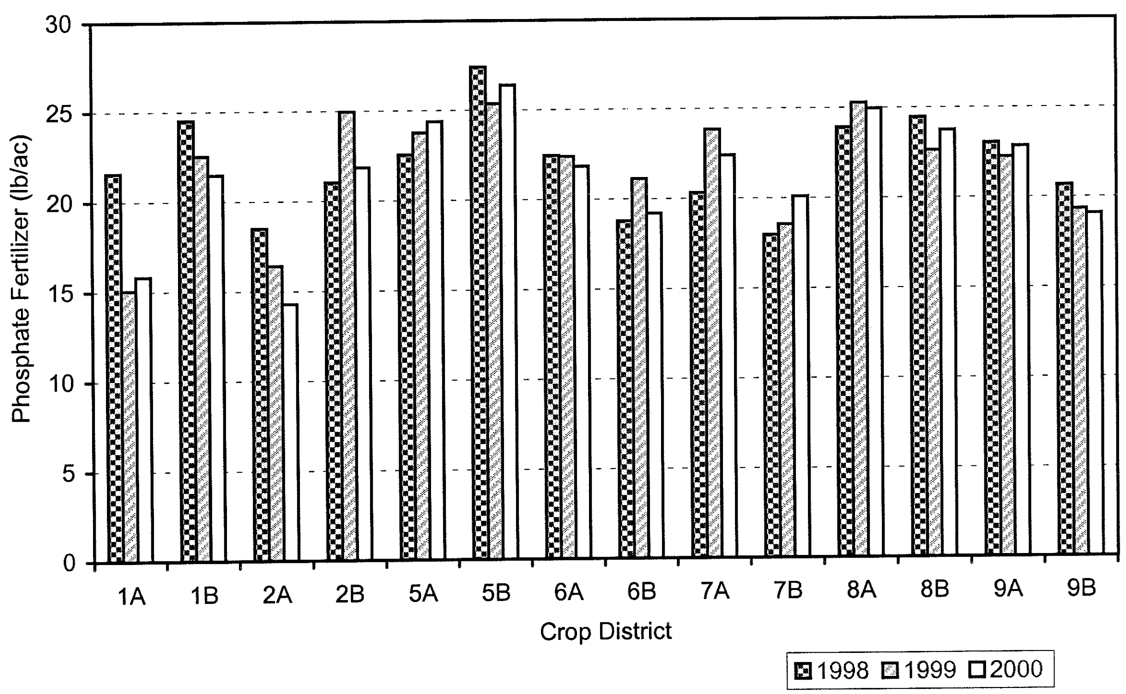


Fig. 4c. Potassium Fertilizer Use by Crop District 1998-2000
Overall Averages: 1998: 2.6 1999: 3.0 2000: 3.2

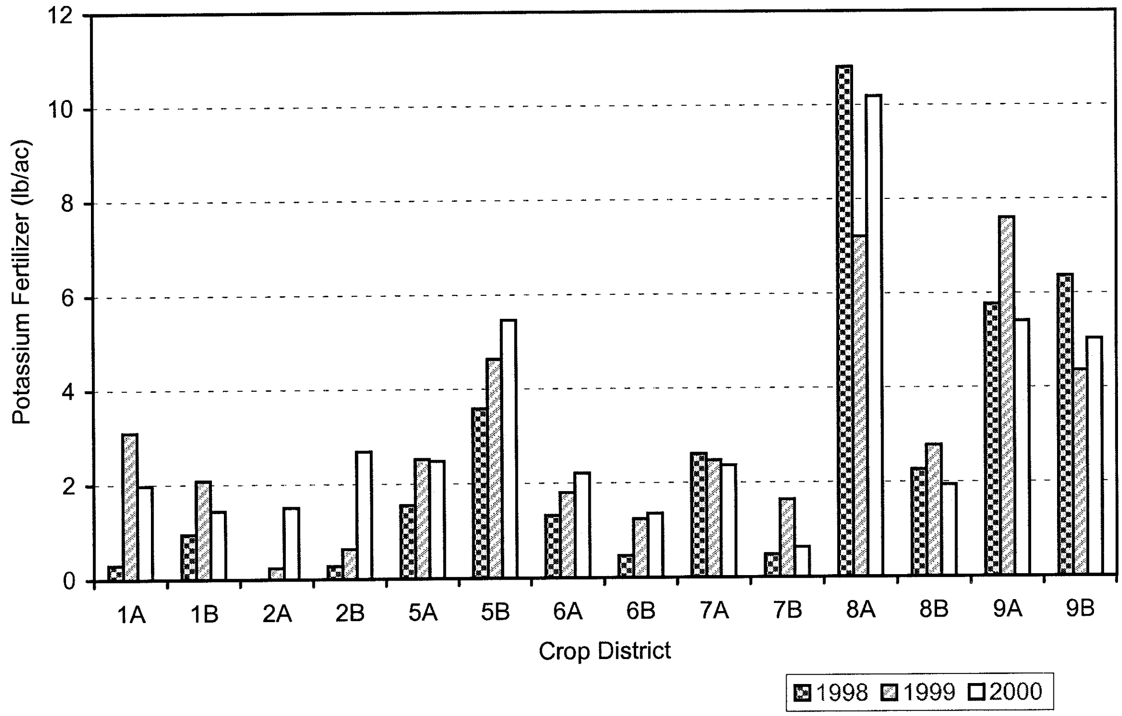


Fig. 4d. Sulphur Fertilizer Use by Crop District 1998-2000
Overall Averages: 1998: 9.3 1999: 10.1 2000: 10.4

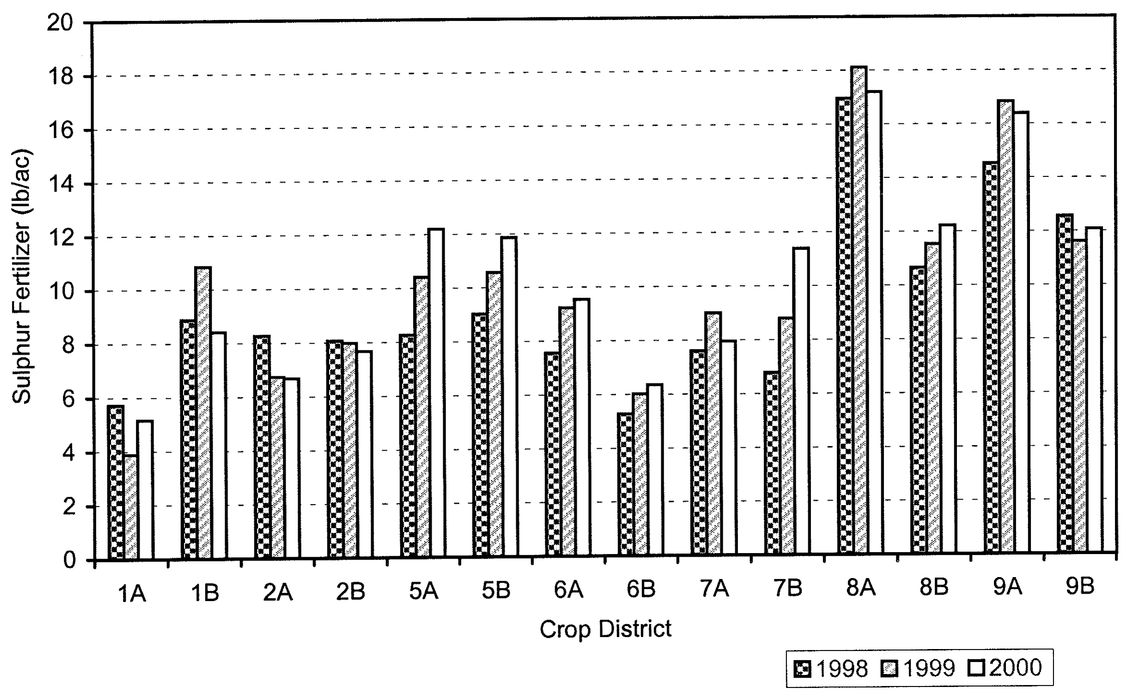


Figure 5a.

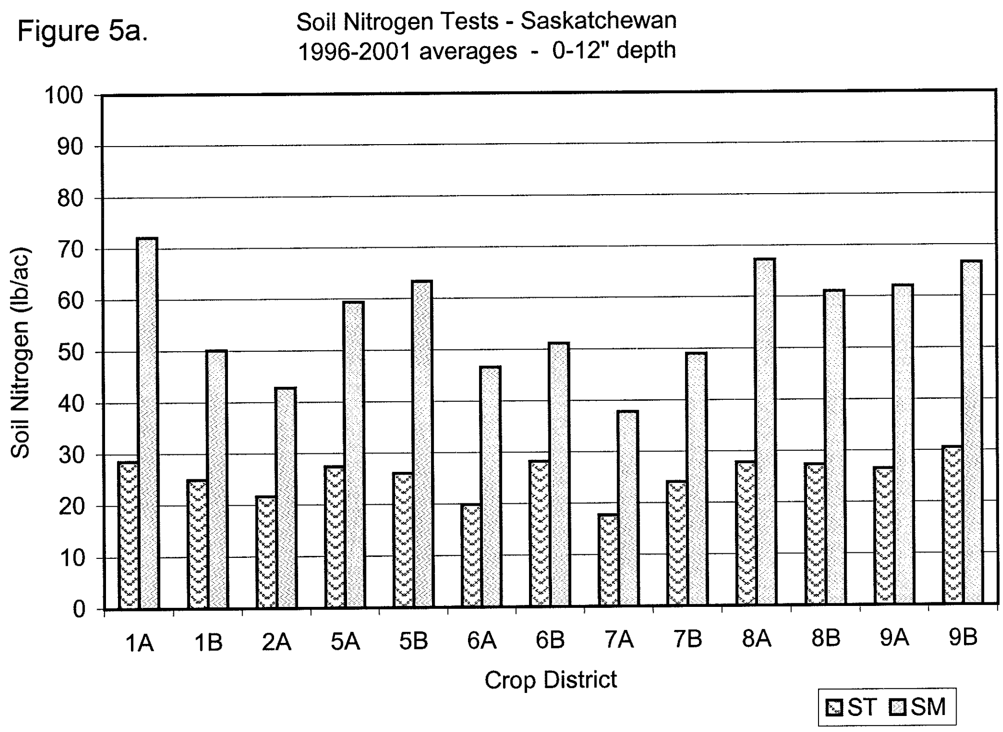


Figure 5b.

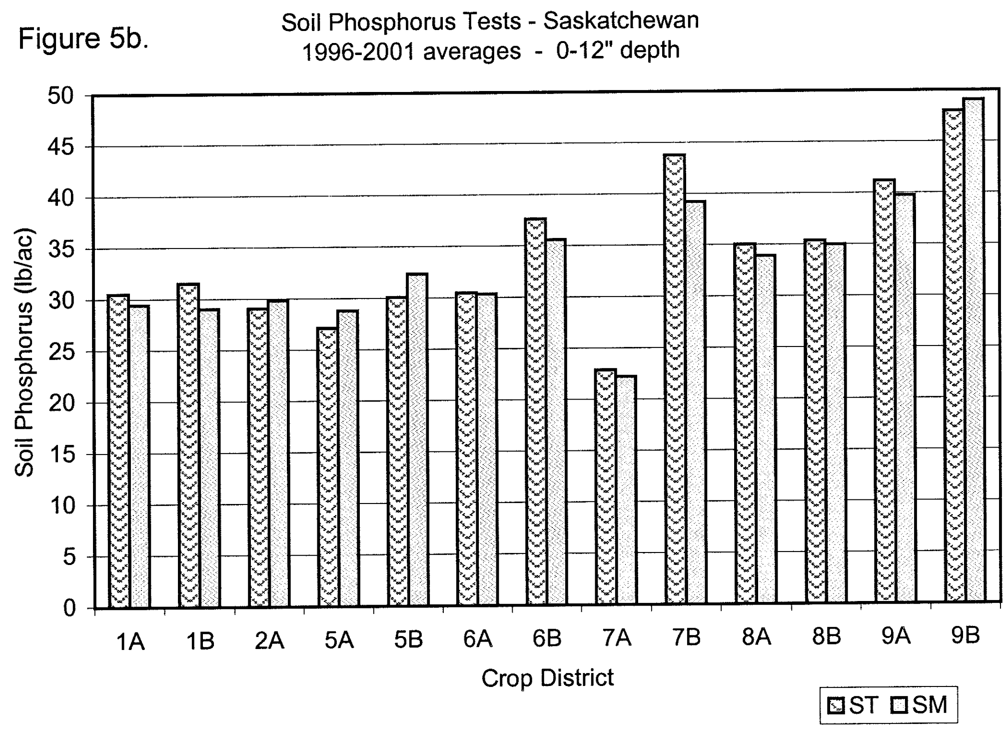


Figure 5c.

Soil Potassium Tests - Saskatchewan
1996-2001 averages - 0-12" depth

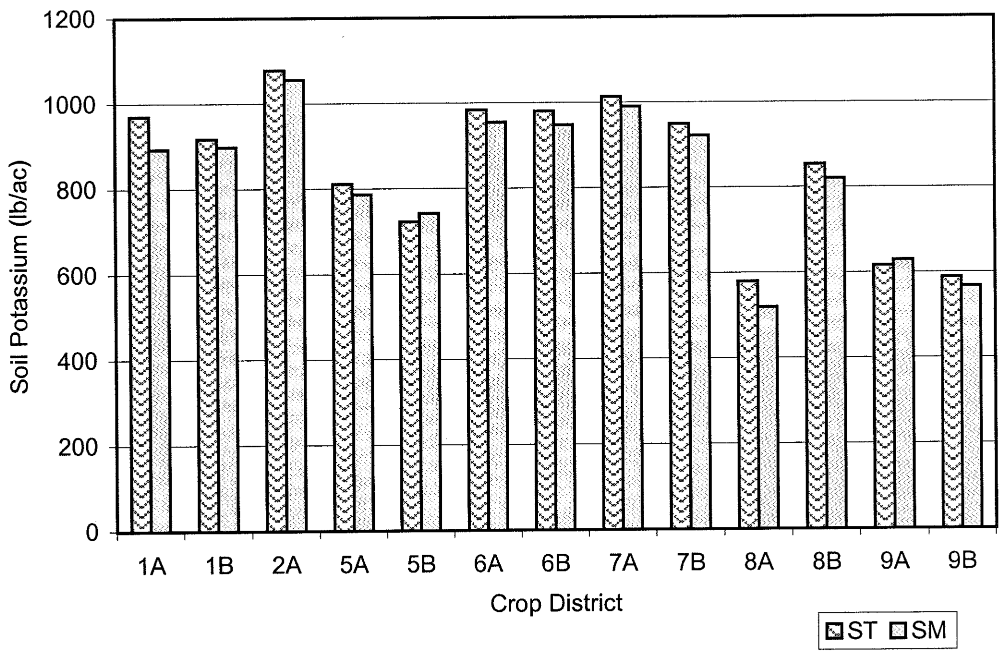


Figure 5d.

Soil Sulphur Tests - Saskatchewan
1996-2001 averages - 0-12" depth

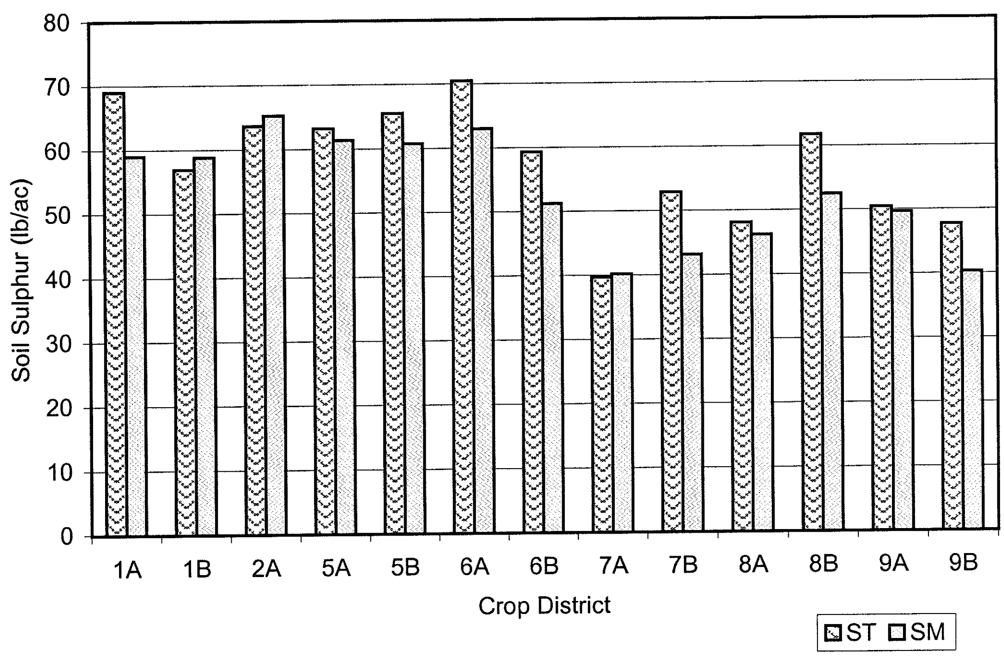
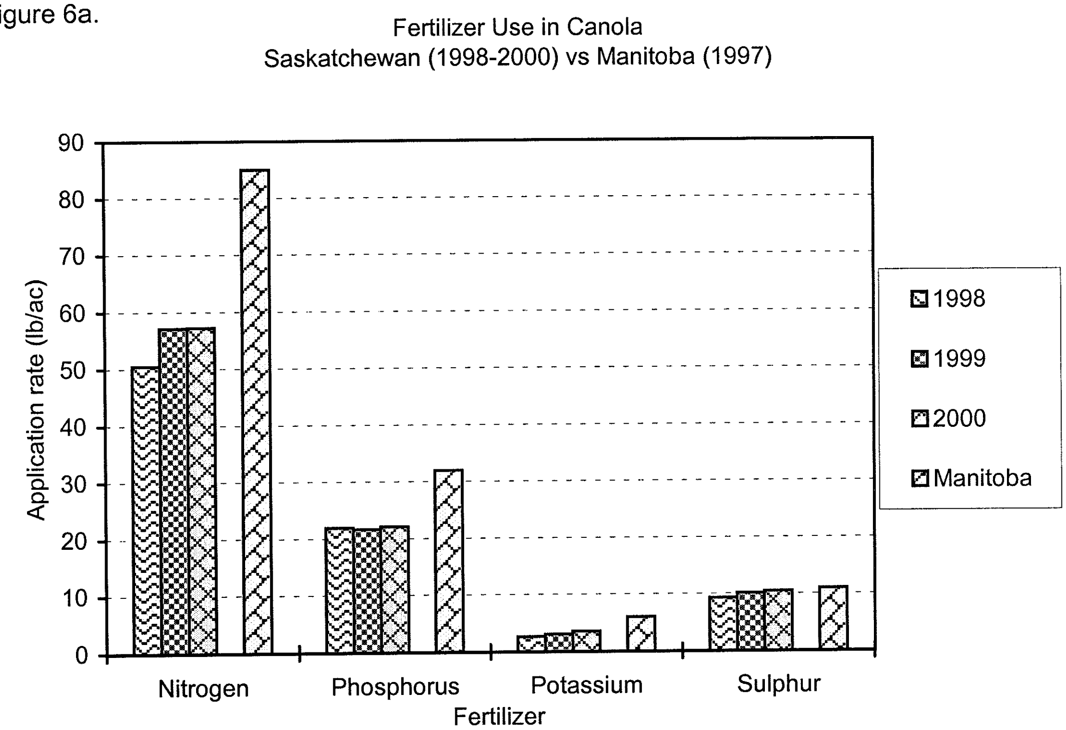
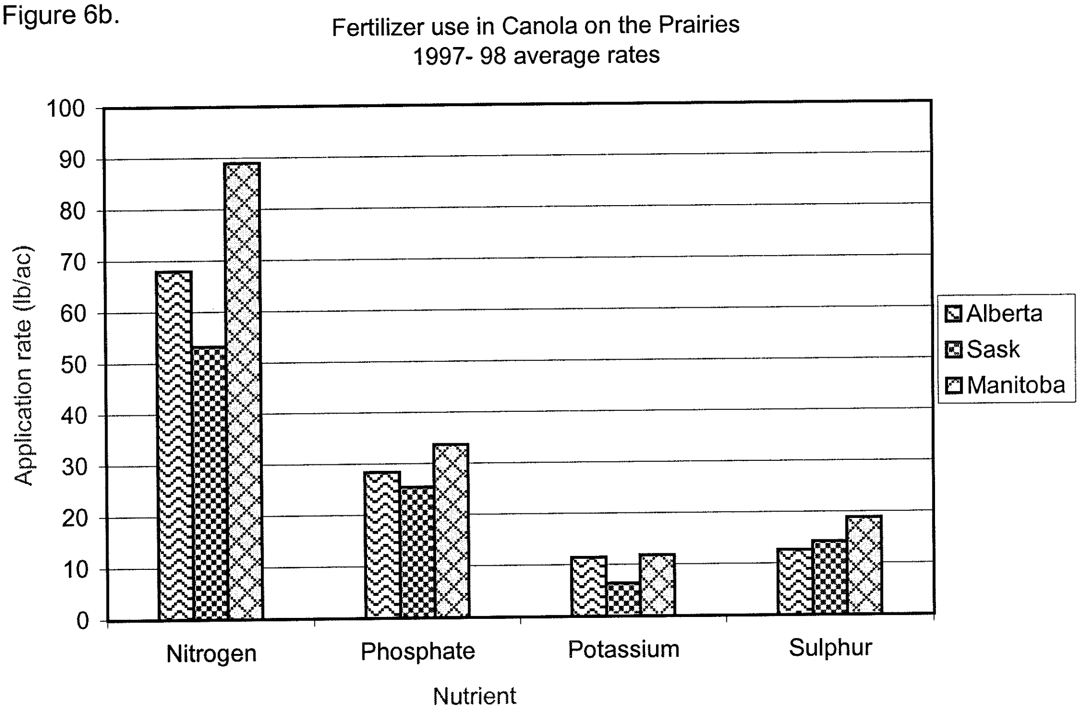


Figure 6a.

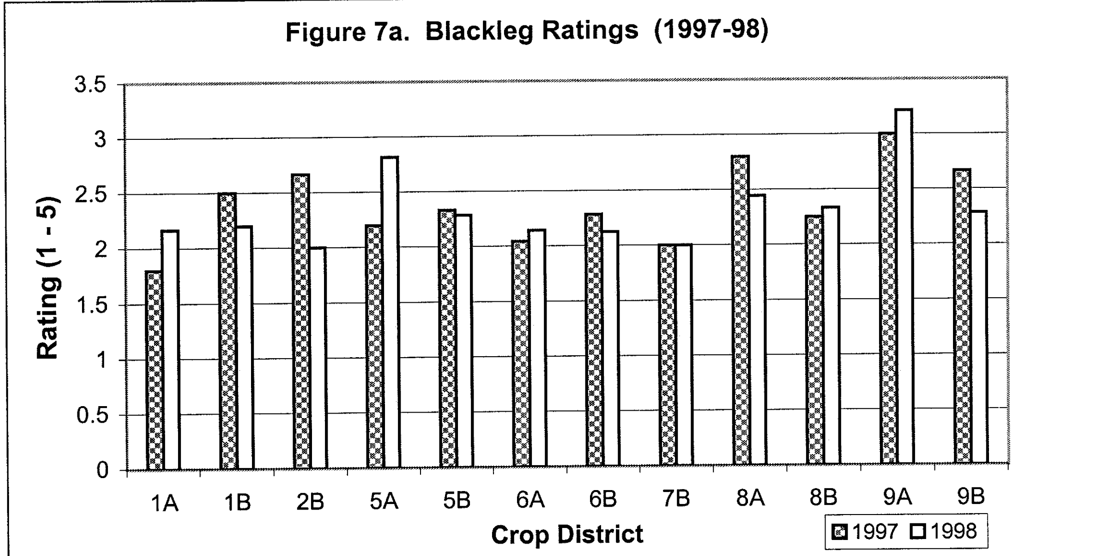


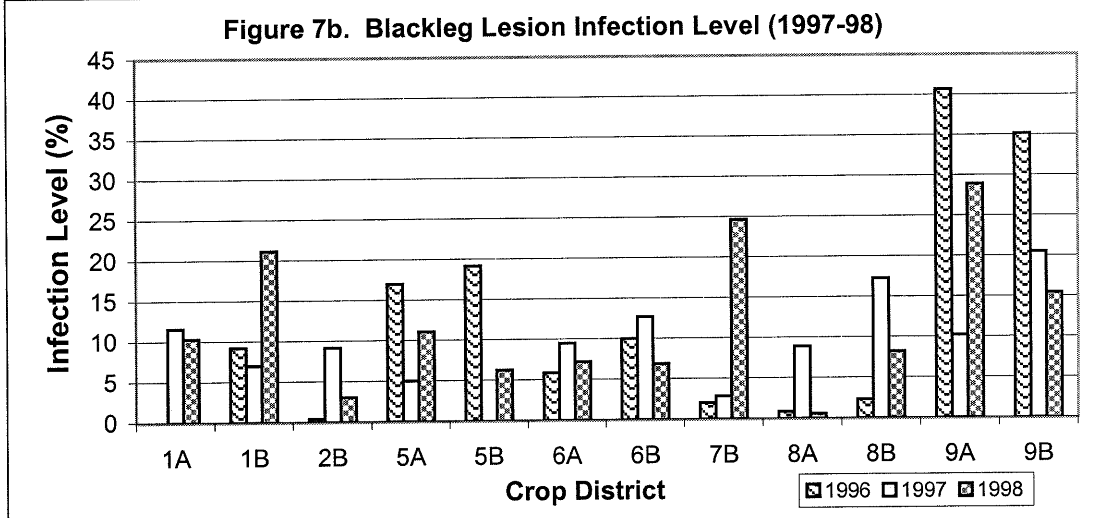
Source: Saskatchewan and Manitoba Management Plus Program

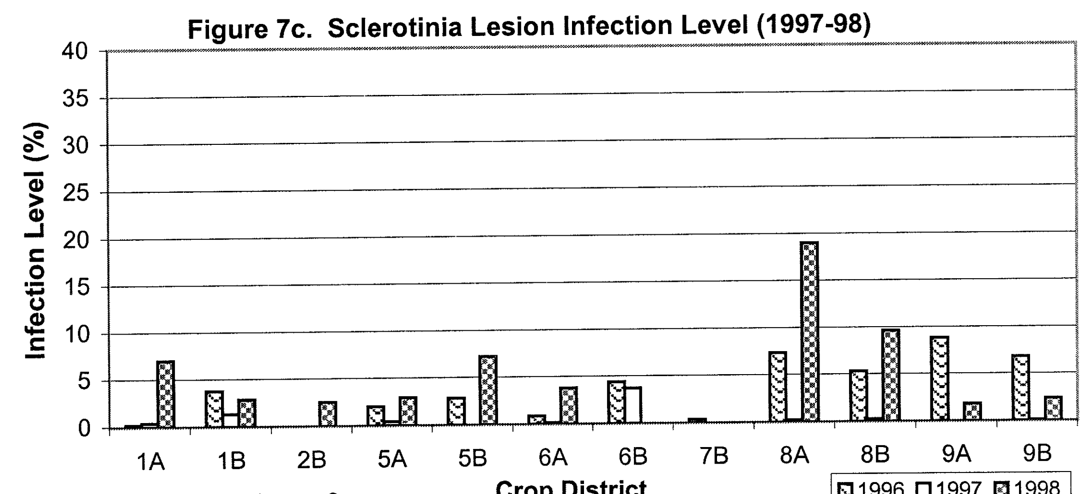
Figure 6b.



Source: 1997-98 Canola Disease Survey







Source: 1996-98 Canola Disease Survey

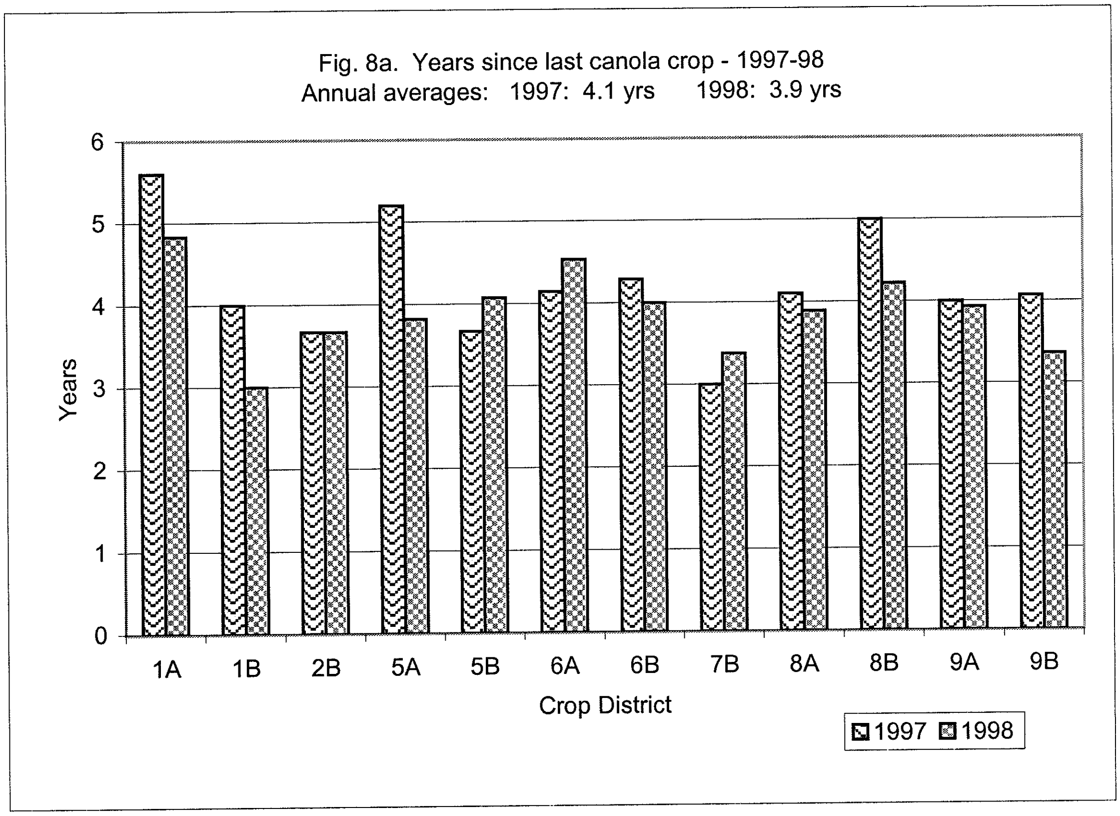


Fig. 8a. Years since last canola crop - 1997-98
Annual averages: 1997: 4.1 yrs 1998: 3.9 yrs
Years
0
1
2
3
4
5
6
1A
1B
2B
5A
5B
6A
6B
7B
8A
8B
9A
9B
Crop District
1997
1998

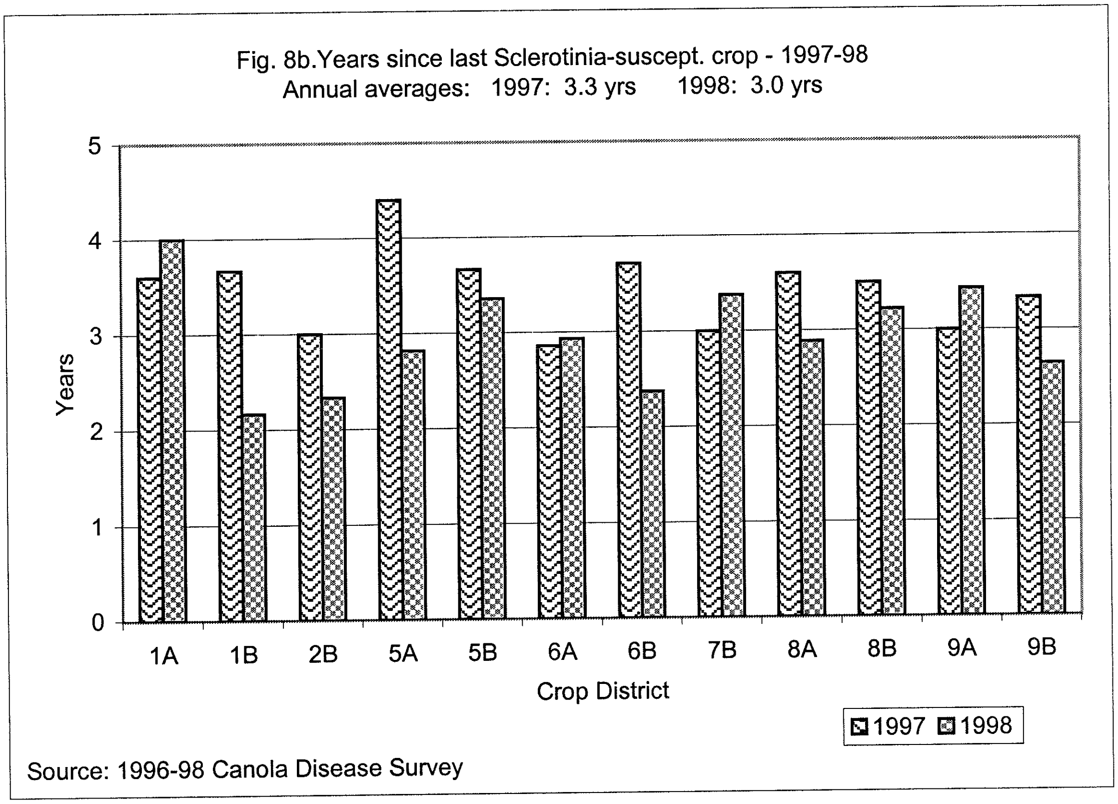
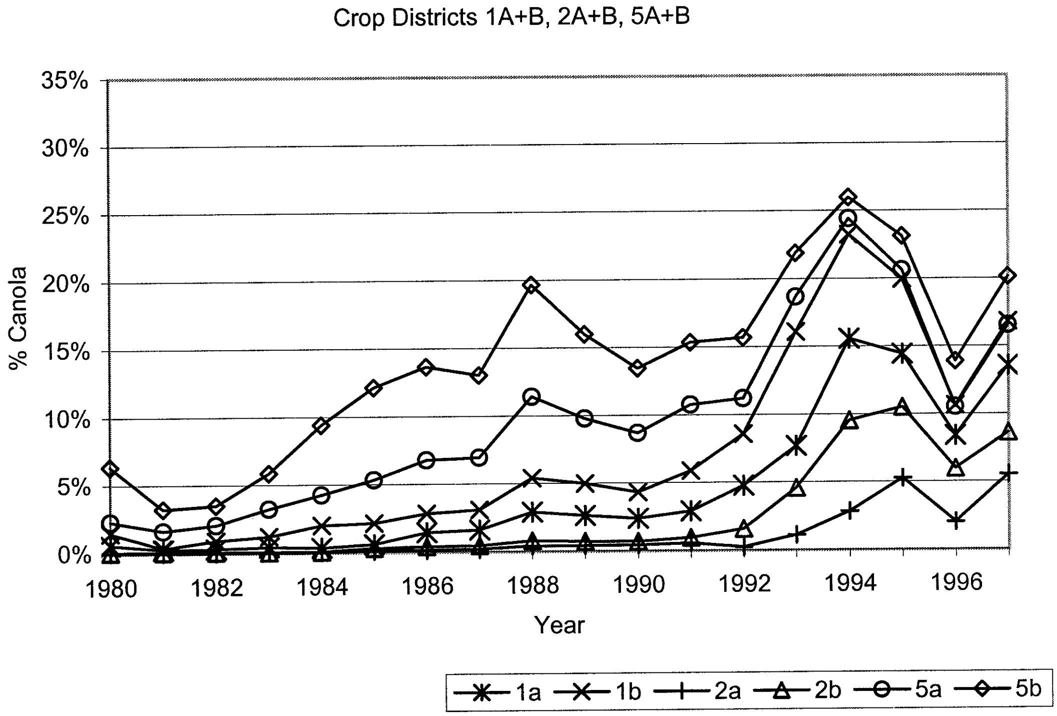


Fig. 8b.Years since last Sclerotinia-suscept. crop - 1997-98
Annual averages: 1997: 3.3 yrs 1998: 3.0 yrs
Years
0
1
2
3
4
5
1A
1B
2B
5A
5B
6A
6B
7B
8A
8B
9A
9B
Crop District
1997
1998
Source: 1996-98 Canola Disease Survey

Figure 9. Percent of seeded acreage in canola for selected crop districts in Saskatchewan.



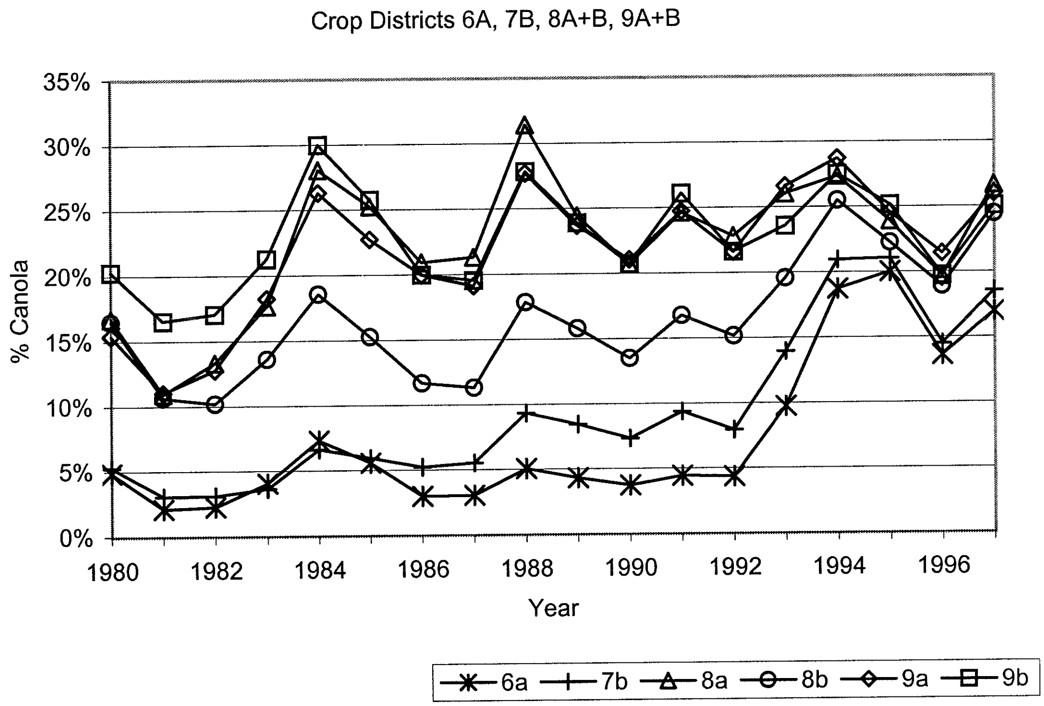
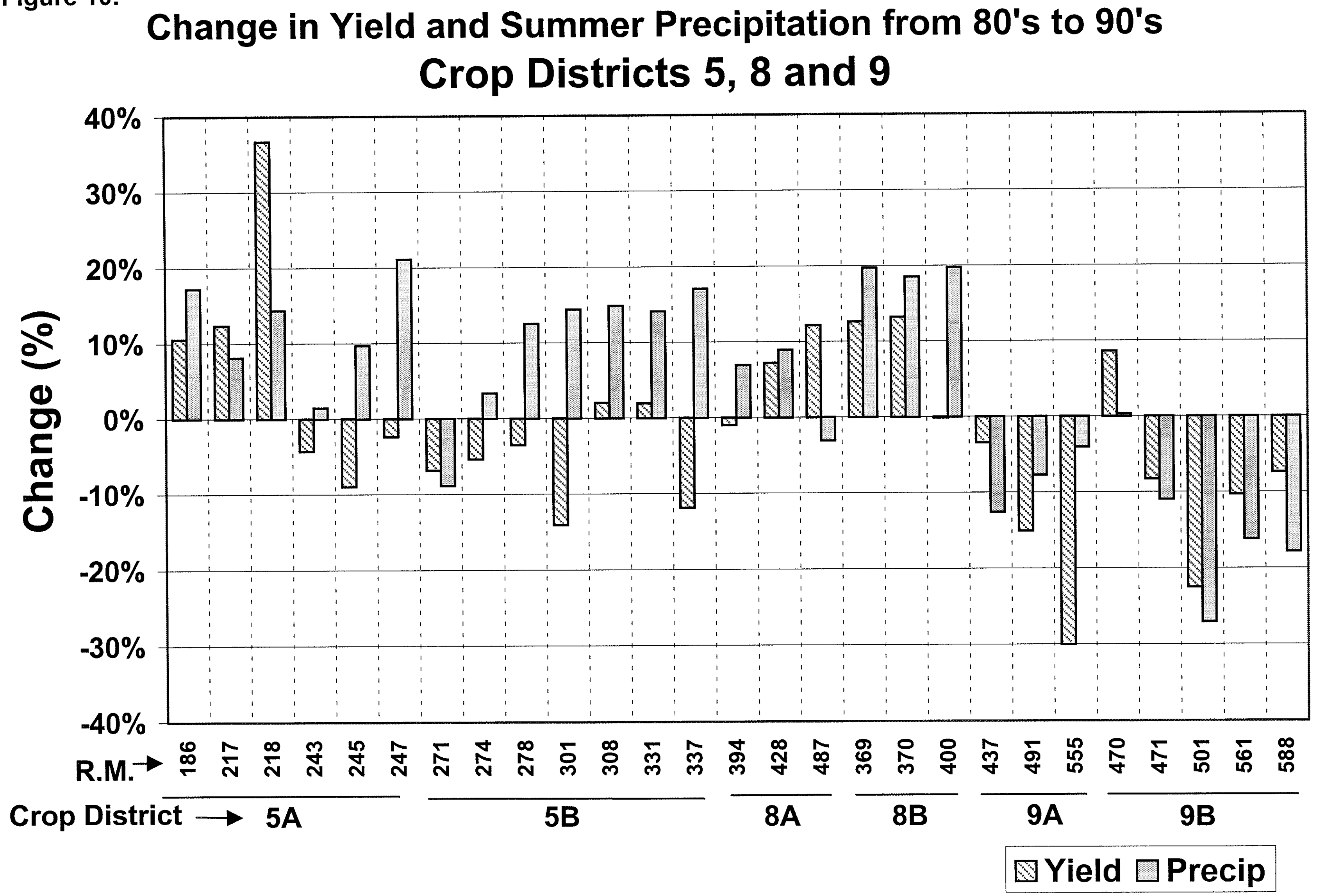


Figure 10.



Change in Yield and Summer Precipitation from 80's to 90's
Crop Districts 5, 8 and 9
Change (%)
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
R.M.
186 217 218 243 245 247 271 274 278 301 308 331 337 394 428 487 369 370 400 437 491 555 470 471 501 561 588
Crop District
5A
5B
8A
8B
9A
9B
Yield
Precip

Figure 11a.

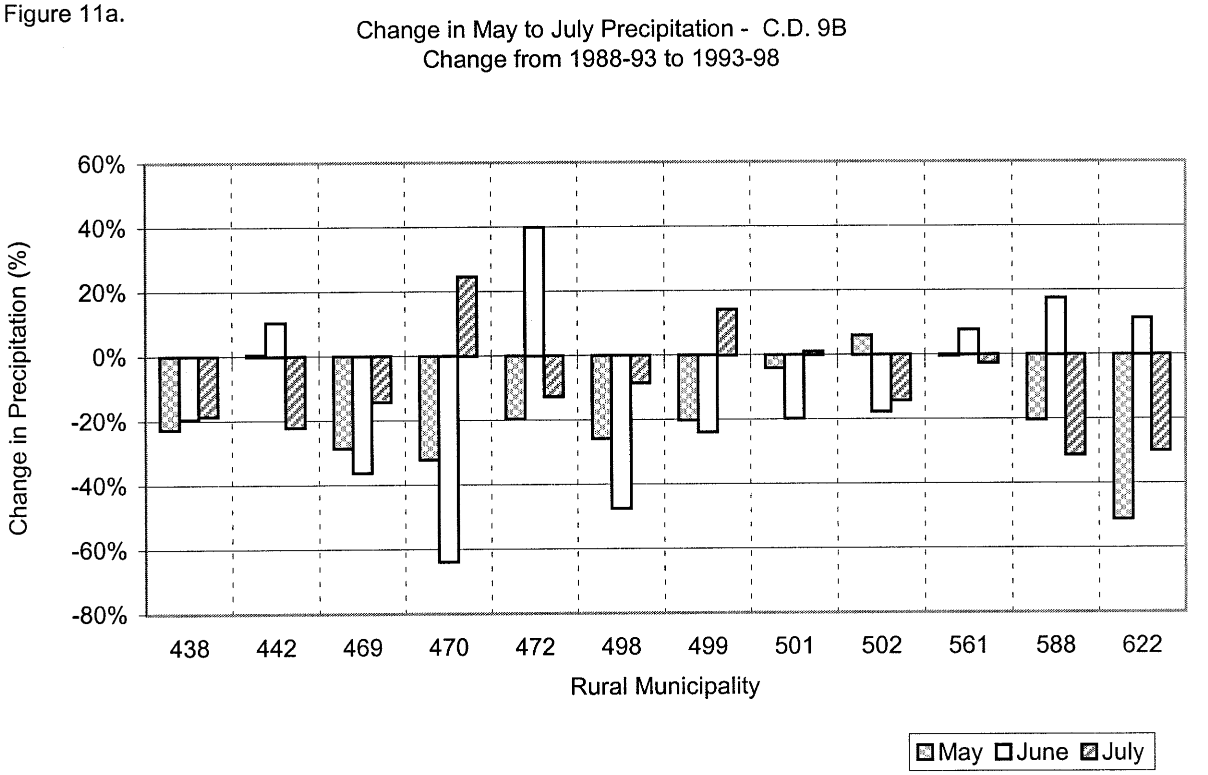


Figure 11b.

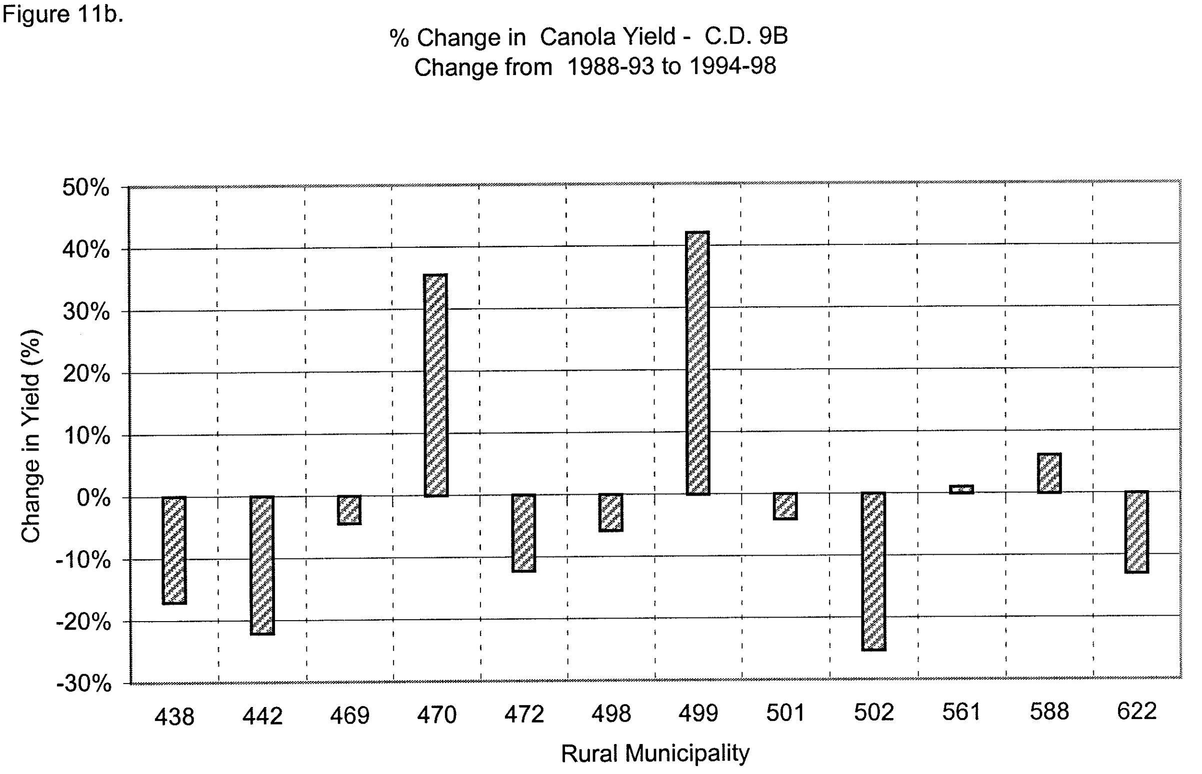
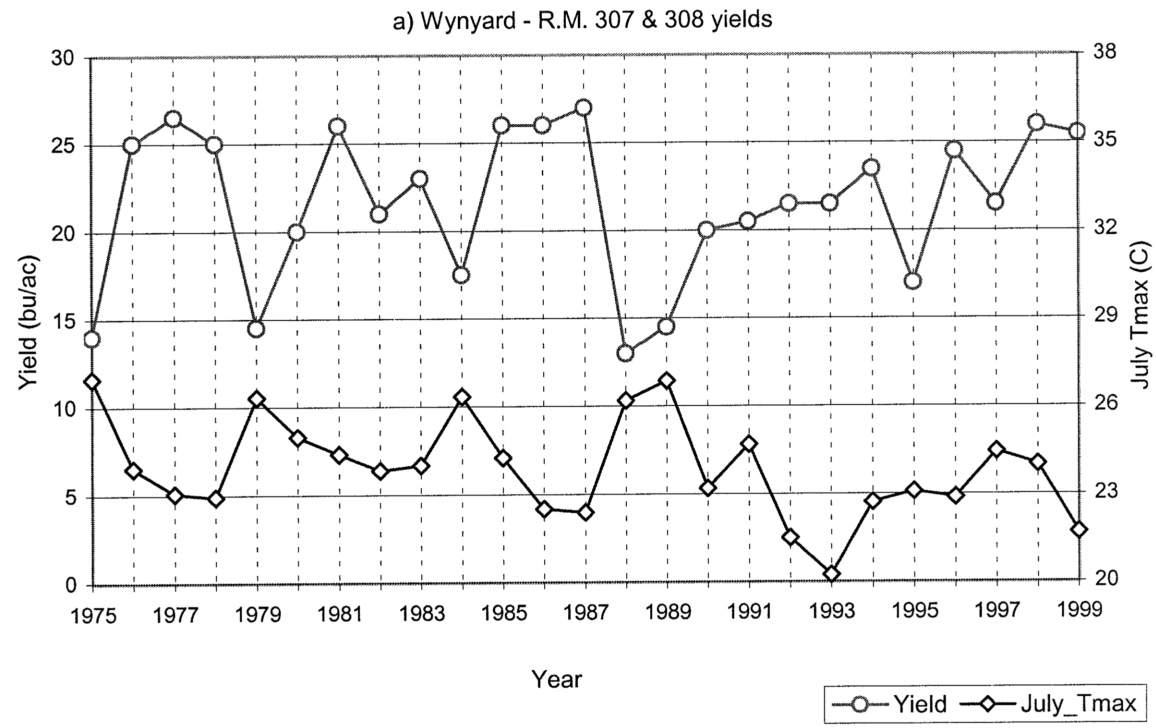


Figure 12. Canola Yields and Mean July Maximum Temperature



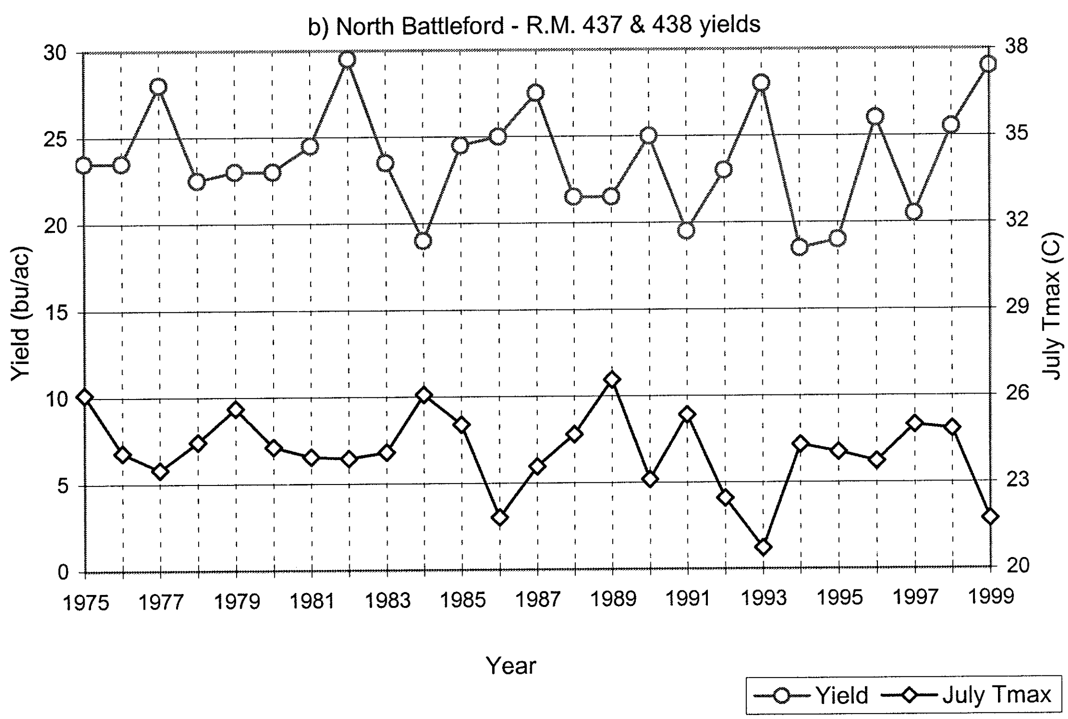


Fig. 13a. Canola Yields vs Soil Moisture - 1999 Field Monitoring

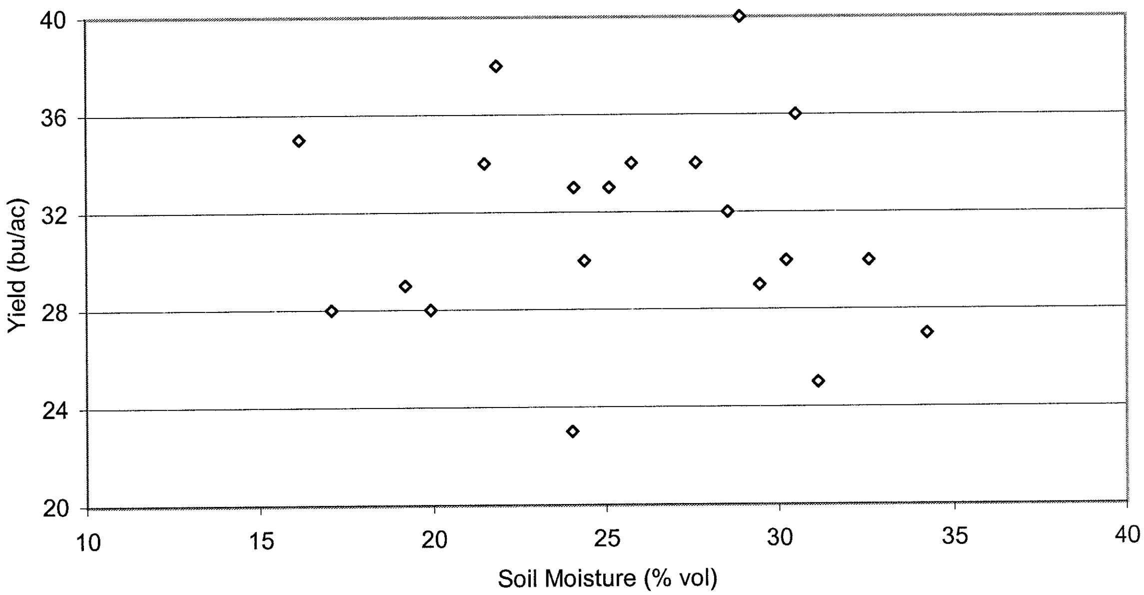


Fig. 13b. Canola Yield vs Total Biomass - 1999 Field Monitoring

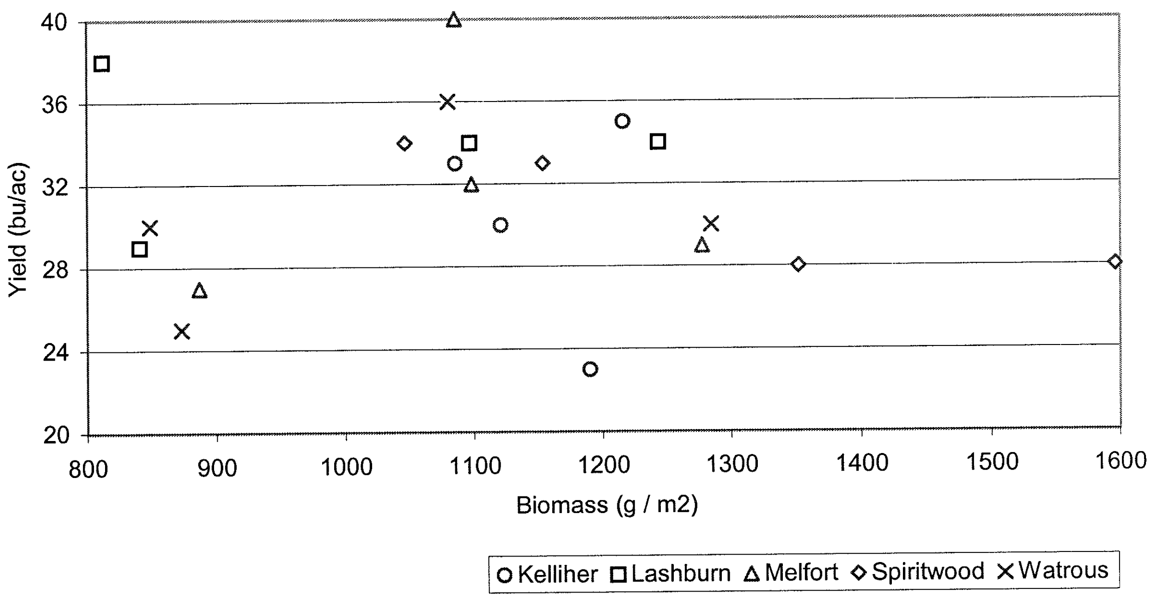


Fig. 14a. Canola Yield vs Fertilizer N applied

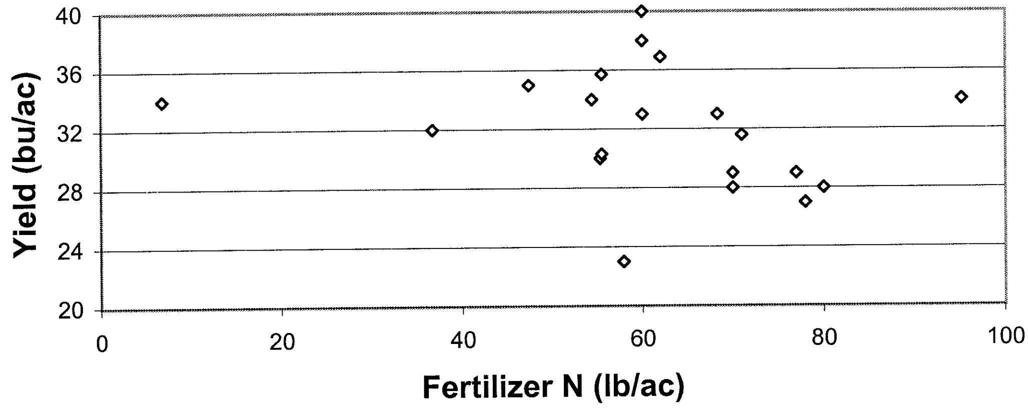


Fig. 14b. Canola Yield vs Fertilizer P applied

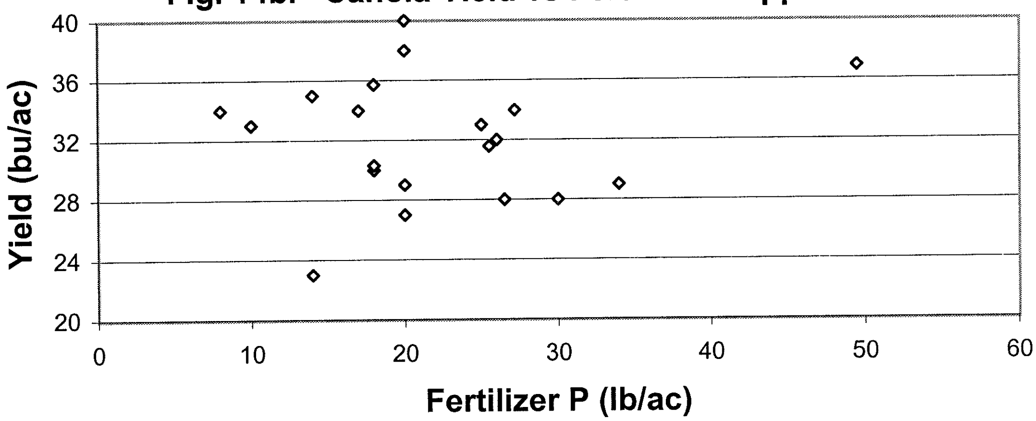


Fig. 14c. Canola Yield vs Fertilizer S applied

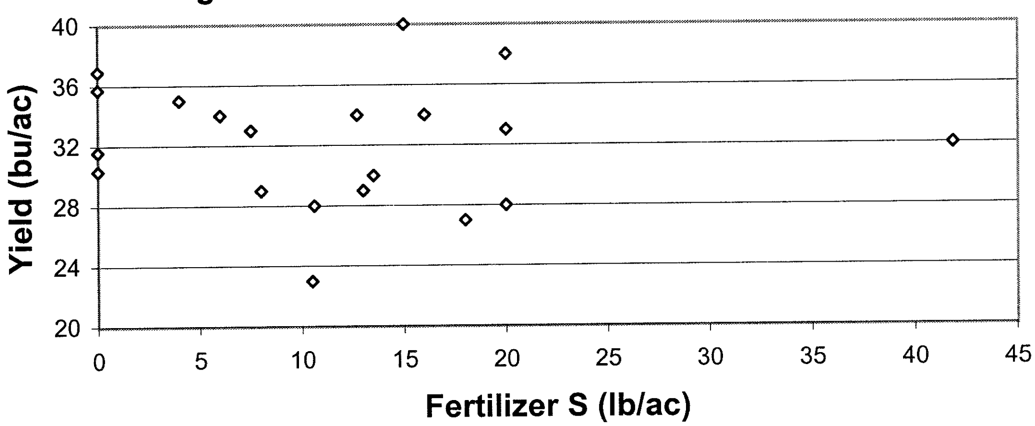
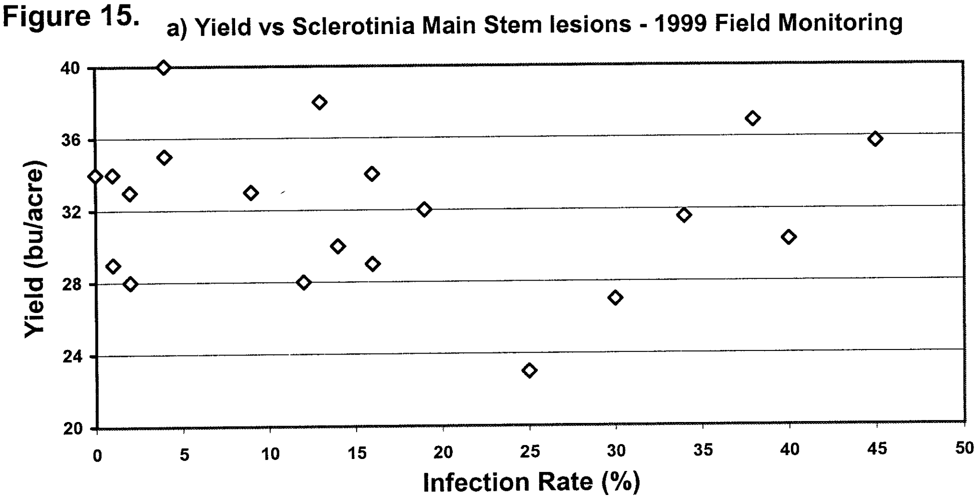
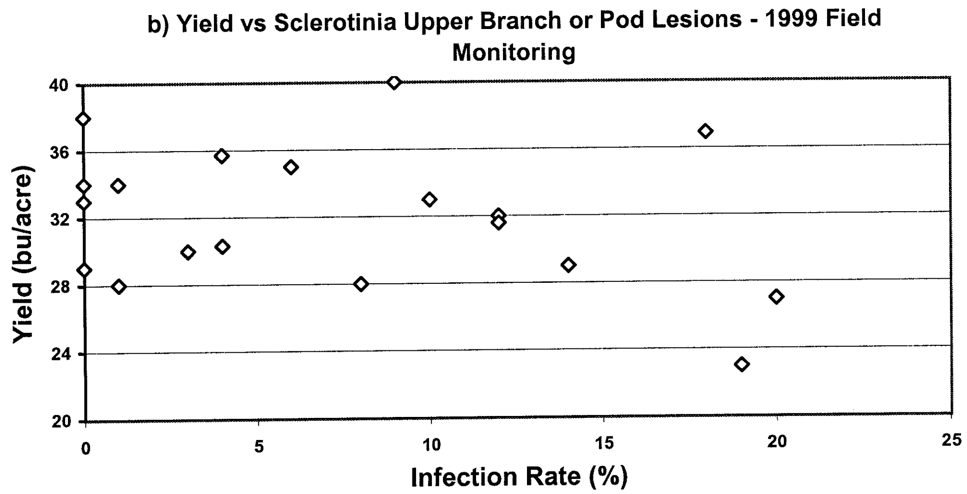


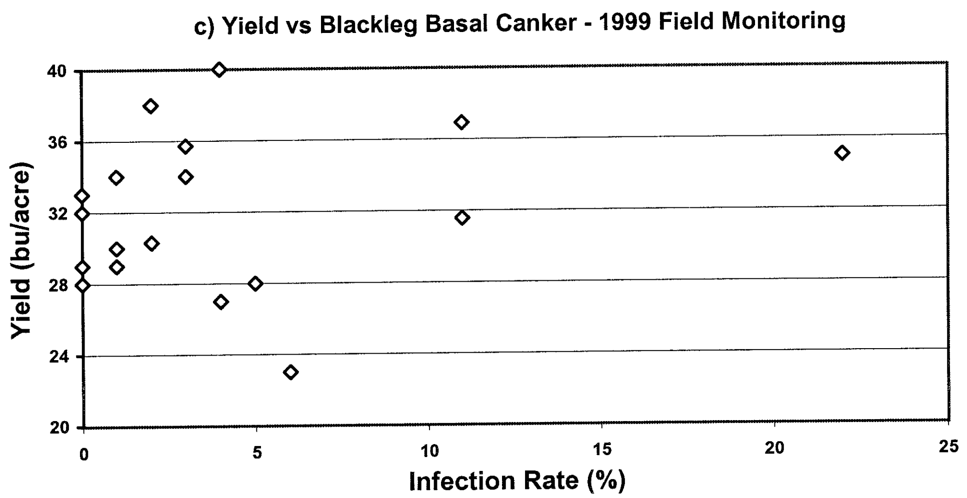
Figure 15.



a) Yield vs Sclerotinia Main Stem lesions - 1999 Field Monitoring
Yield (bu/acre)
40
36
32
28
24
20
0
5
10
15
20
25
30
35
40
45
50
Infection Rate (%)



b) Yield vs Sclerotinia Upper Branch or Pod Lesions - 1999 Field Monitoring
Yield (bu/acre)
40
36
32
28
24
20
0
5
10
15
20
25
Infection Rate (%)



c) Yield vs Blackleg Basal Canker - 1999 Field Monitoring
Yield (bu/acre)
40
36
32
28
24
20
0
5
10
15
20
25
Infection Rate (%)

Figure 16. Canola Heat Stress Experiment Field Layout - 2001.

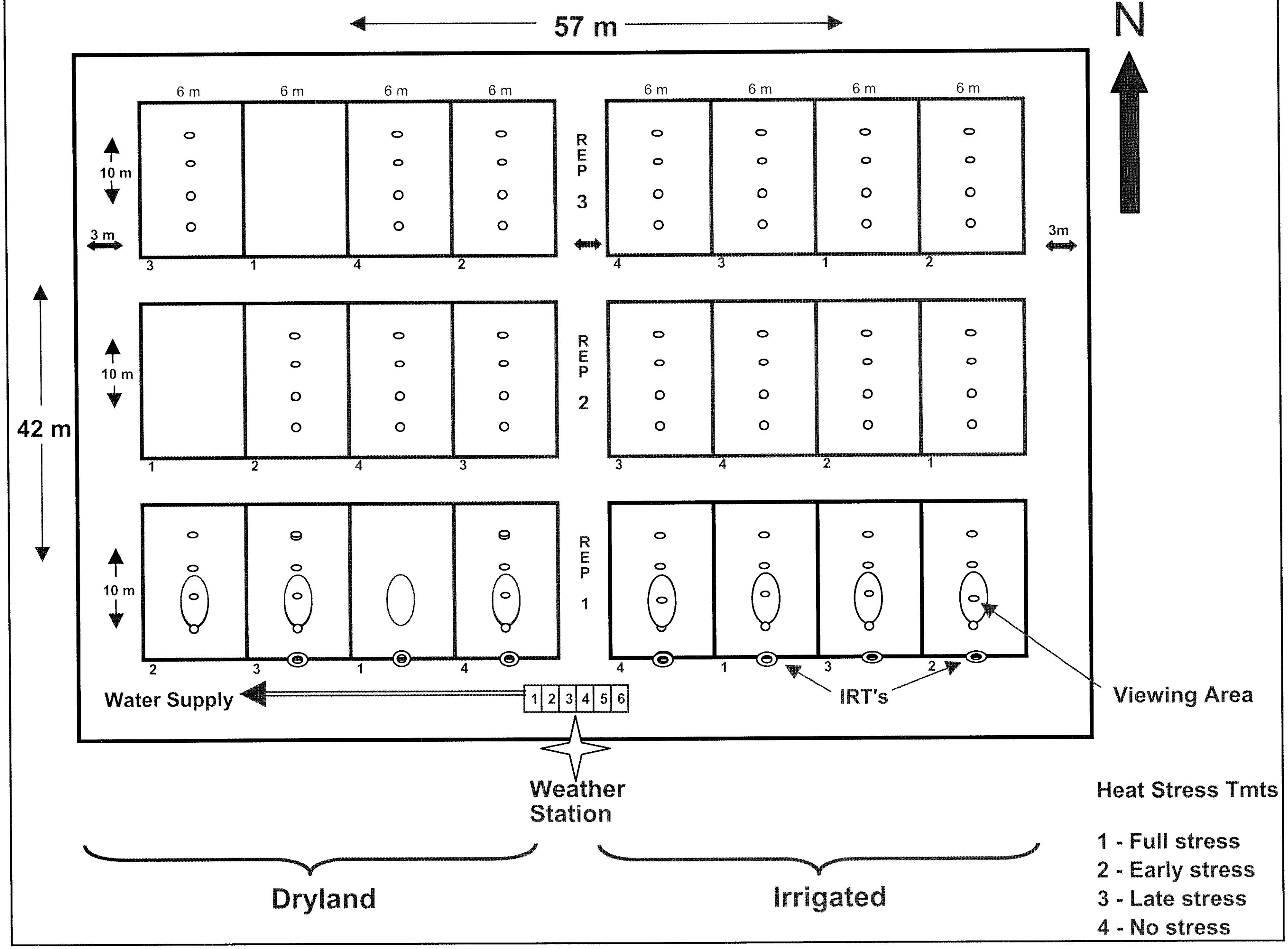
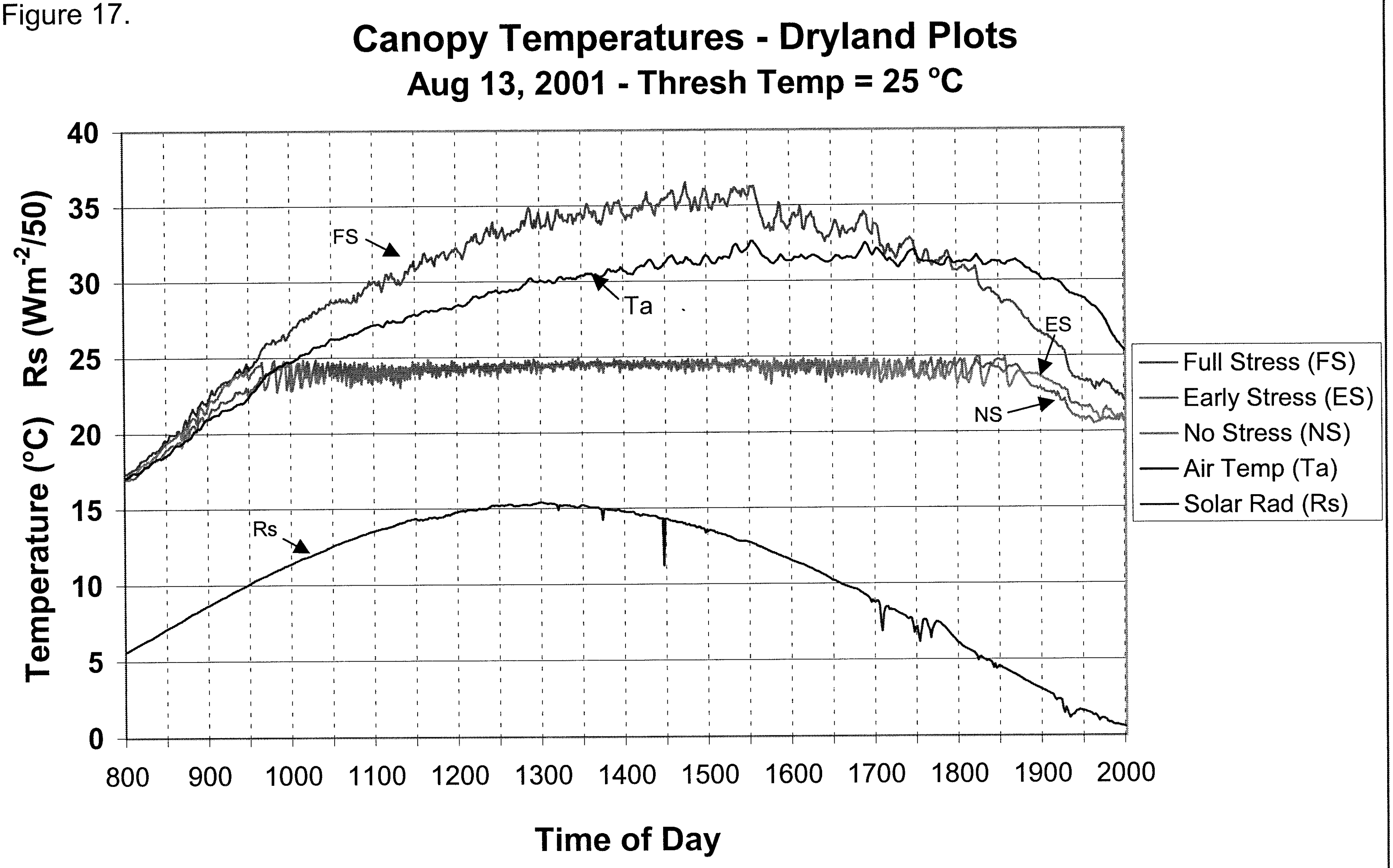
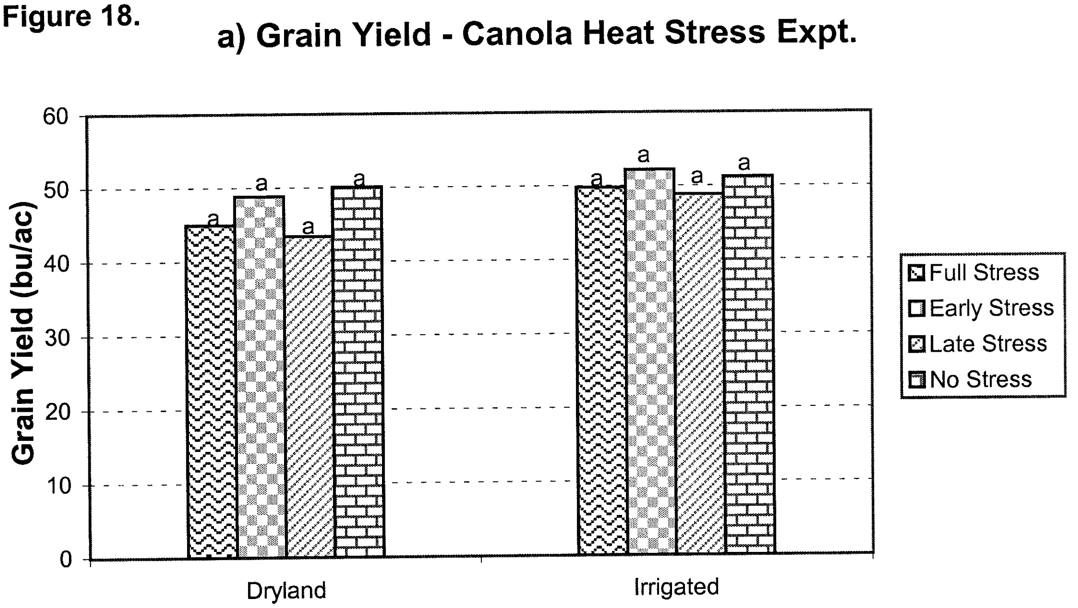


Figure 17.

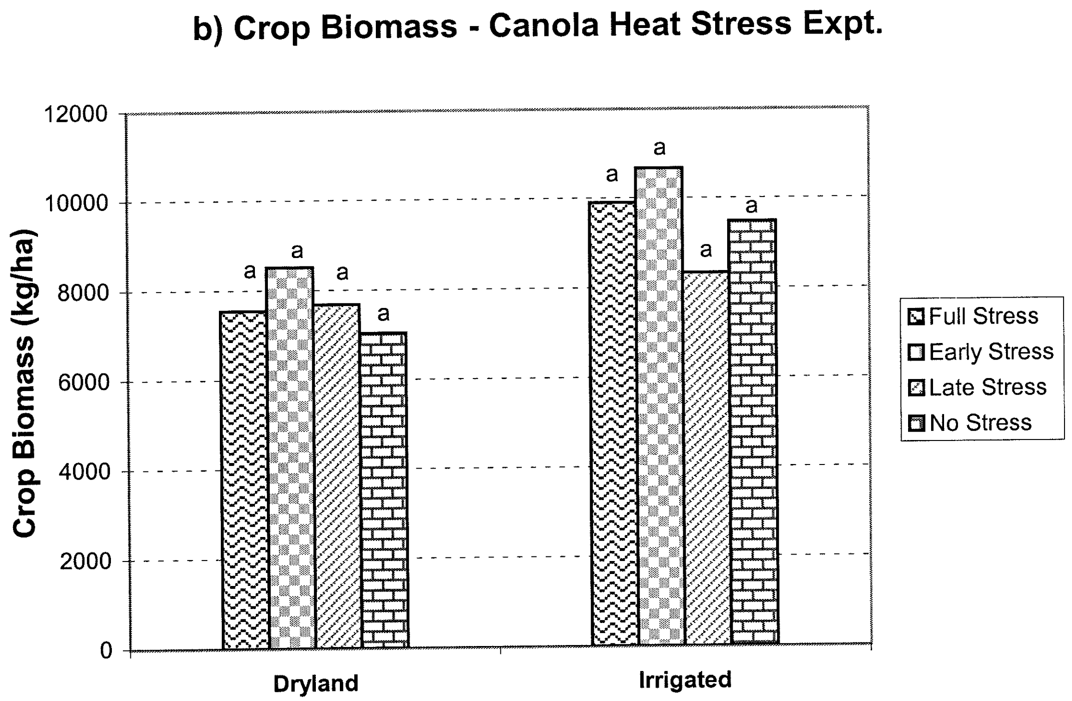


Canopy Temperatures - Dryland Plots
Aug 13, 2001 - Thresh Temp = 25 °C
Temperature (°C) Rs (Wm-2/50)
40
35
30
25
20
15
10
5
0
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Time of Day
FS
Ta
ES
NS
Rs
Full Stress (FS)
Early Stress (ES)
No Stress (NS)
Air Temp (Ta)
Solar Rad (Rs)

Figure 18.



a) Grain Yield - Canola Heat Stress Expt.
Grain Yield (bu/ac)
60
50
40
30
20
10
0
a
a
a
a
a
a
a
a
Dryland
Irrigated
Full Stress
Early Stress
Late Stress
No Stress



b) Crop Biomass - Canola Heat Stress Expt.
Crop Biomass (kg/ha)
12000
10000
8000
6000
4000
2000
0
a
a
a
a
a
a
a
a
Dryland
Irrigated
Full Stress
Early Stress
Late Stress
No Stress

Figure 19.

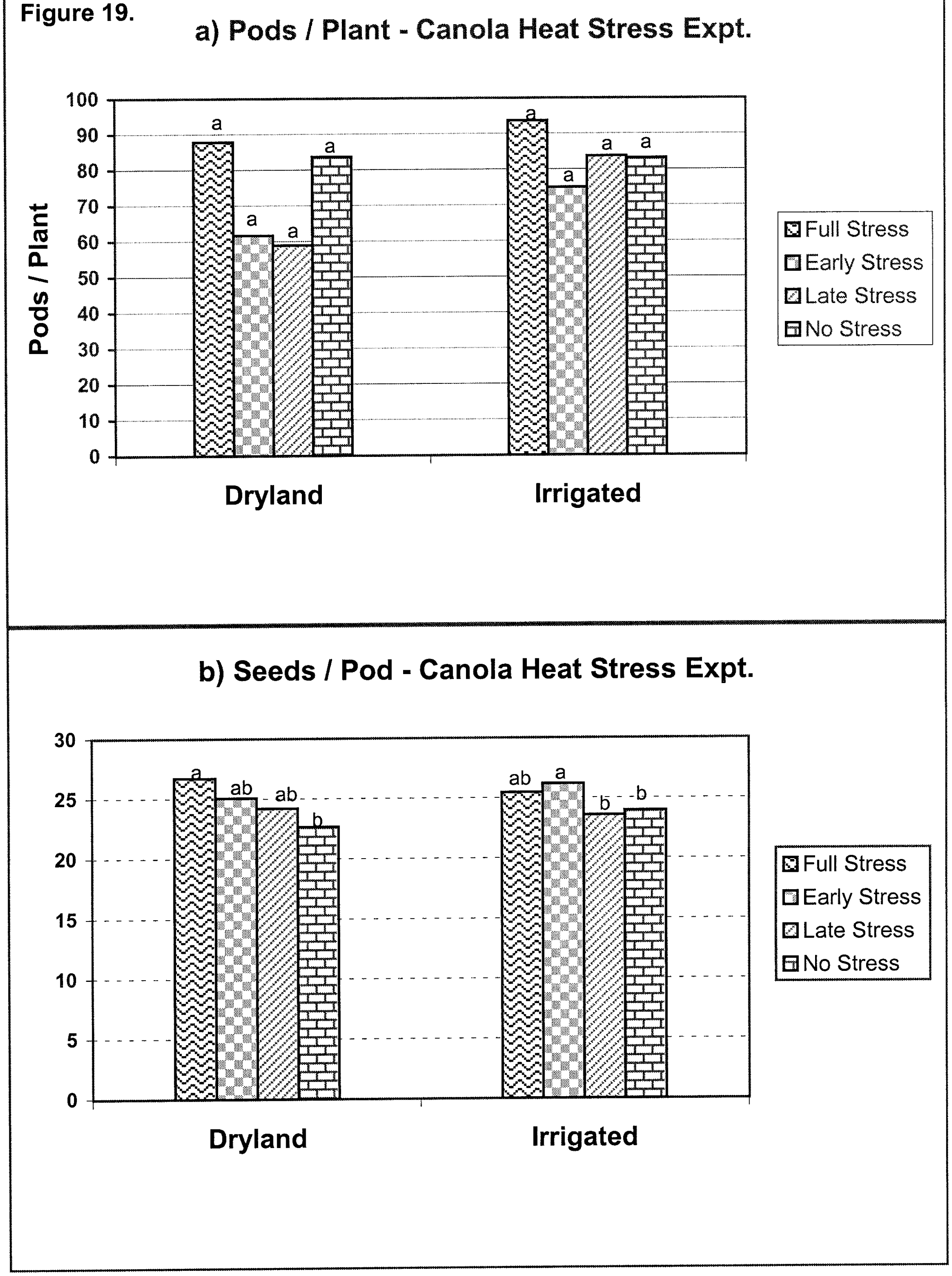
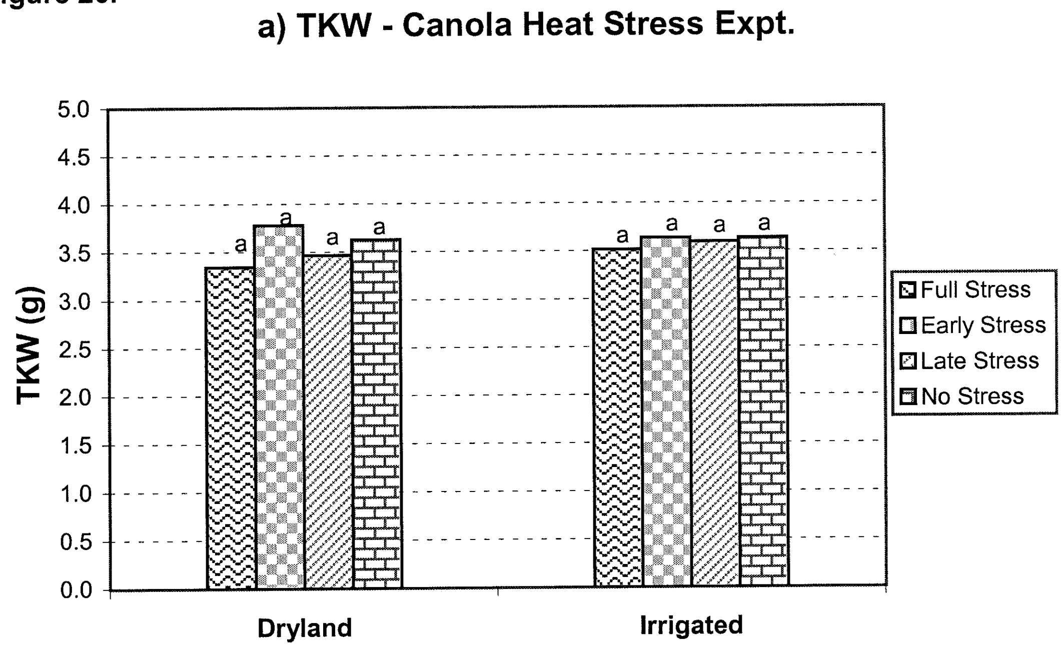
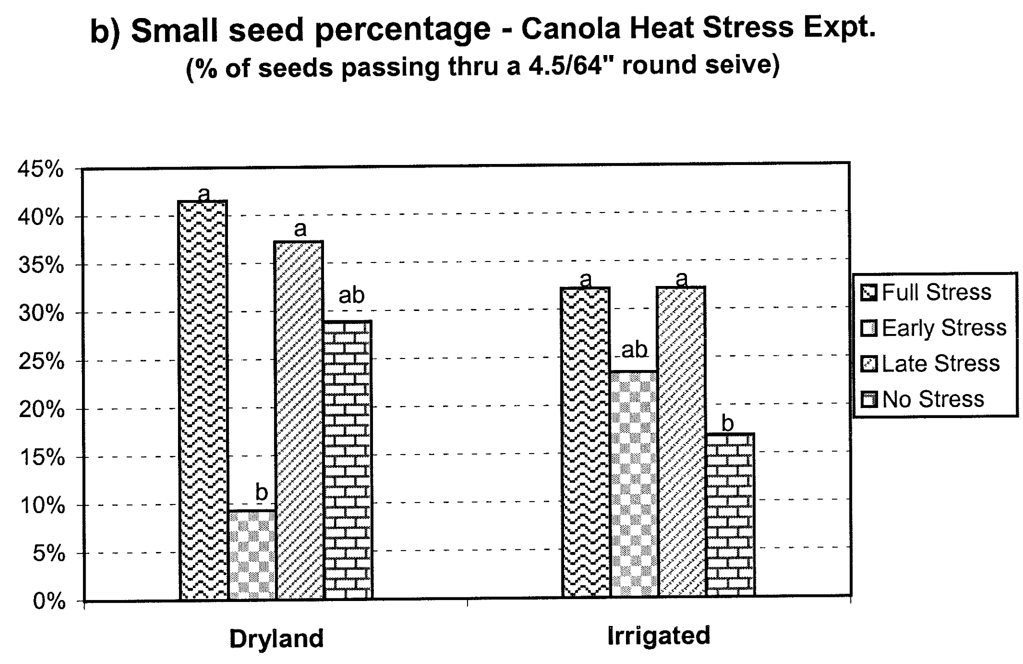

a) Pods / Plant - Canola Heat Stress Expt.
Pods / Plant
100
90
80
70
60
50
40
30
20
10
0
a
a
a
a
a
a
a
a
Dryland
Irrigated
Full Stress
Early Stress
Late Stress
No Stress
b) Seeds / Pod - Canola Heat Stress Expt.
30
25
20
15
10
5
0
a
ab
ab
b
ab
a
b
b
Dryland
Irrigated
Full Stress
Early Stress
Late Stress
No Stress

Figure 20.

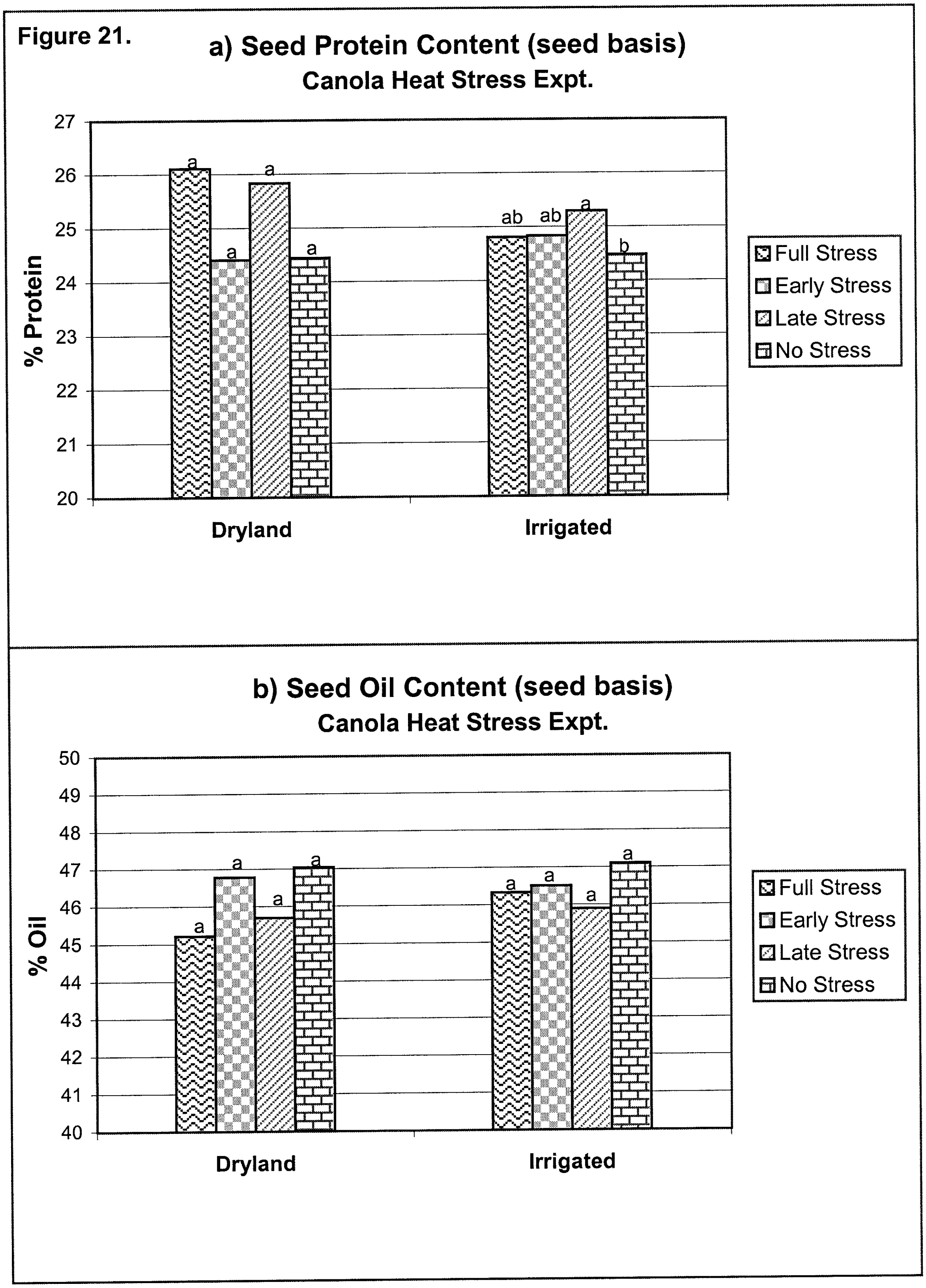


a) TKW - Canola Heat Stress Expt.
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
TKW (g)
a
a
a
a
a
a
a
a
Dryland
Irrigated
Full Stress
Early Stress
Late Stress
No Stress



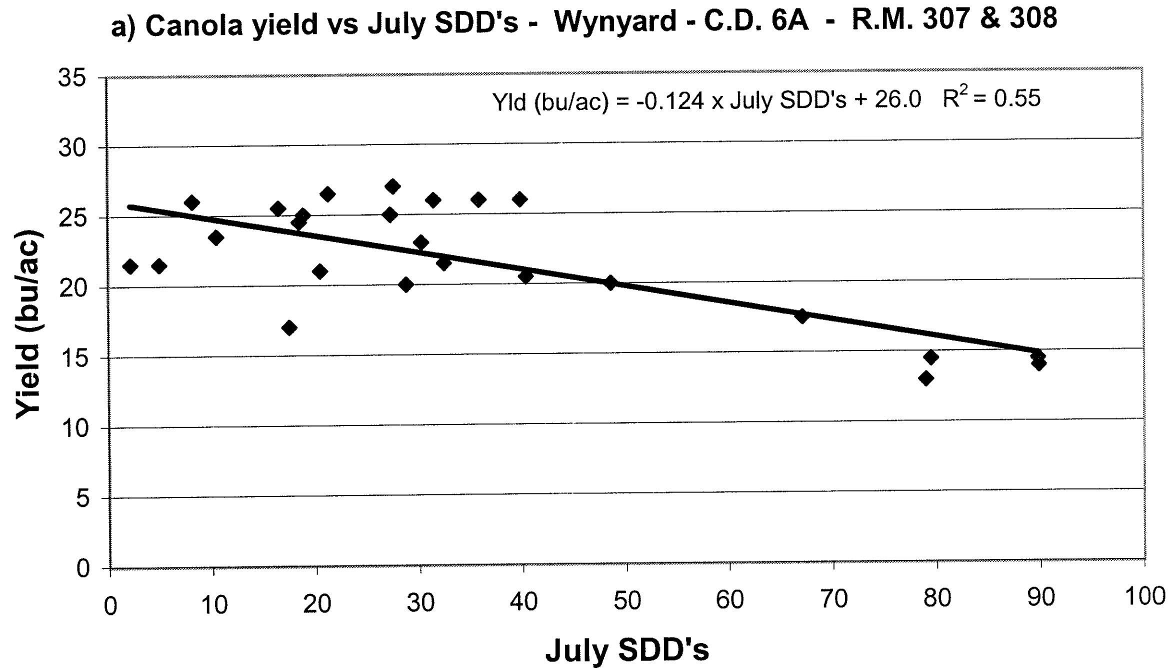
b) Small seed percentage - Canola Heat Stress Expt.
(% of seeds passing thru a 4.5/64" round seive)
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
a
b
a
ab
a
ab
a
b
Dryland
Irrigated
Full Stress
Early Stress
Late Stress
No Stress

Figure 21.



a) Seed Protein Content (seed basis)
Canola Heat Stress Expt.
27
26
25
24
23
22
21
20
% Protein
a
a
a
a
ab
ab
a
b
Dryland
Irrigated
Full Stress
Early Stress
Late Stress
No Stress
b) Seed Oil Content (seed basis)
Canola Heat Stress Expt.
50
49
48
47
46
45
44
43
42
41
40
% Oil
a
a
a
a
a
a
a
a
Dryland
Irrigated
Full Stress
Early Stress
Late Stress
No Stress

Figure 22.


a) Canola yield vs July SDD's - Wynyard - C.D. 6A - R.M. 307 & 308
Yld (bu/ac) = -0.124 x July SDD's + 26.0 R^2 = 0.55
Yield (bu/ac)
July SDD's

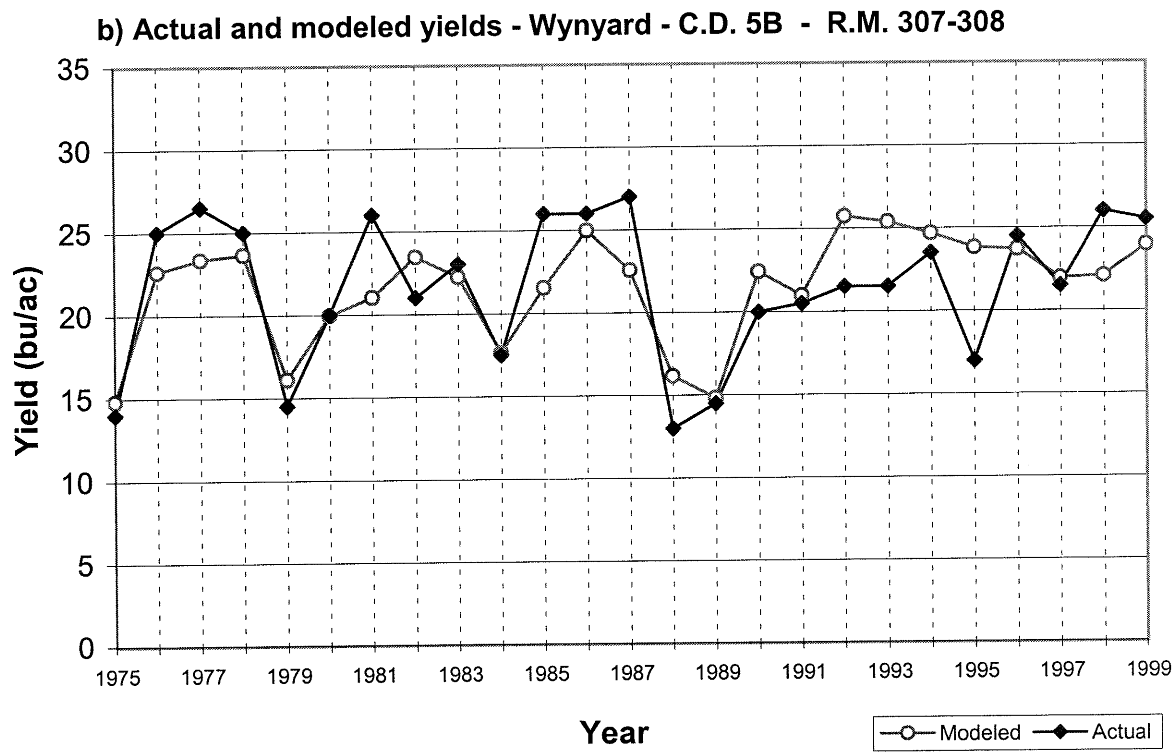
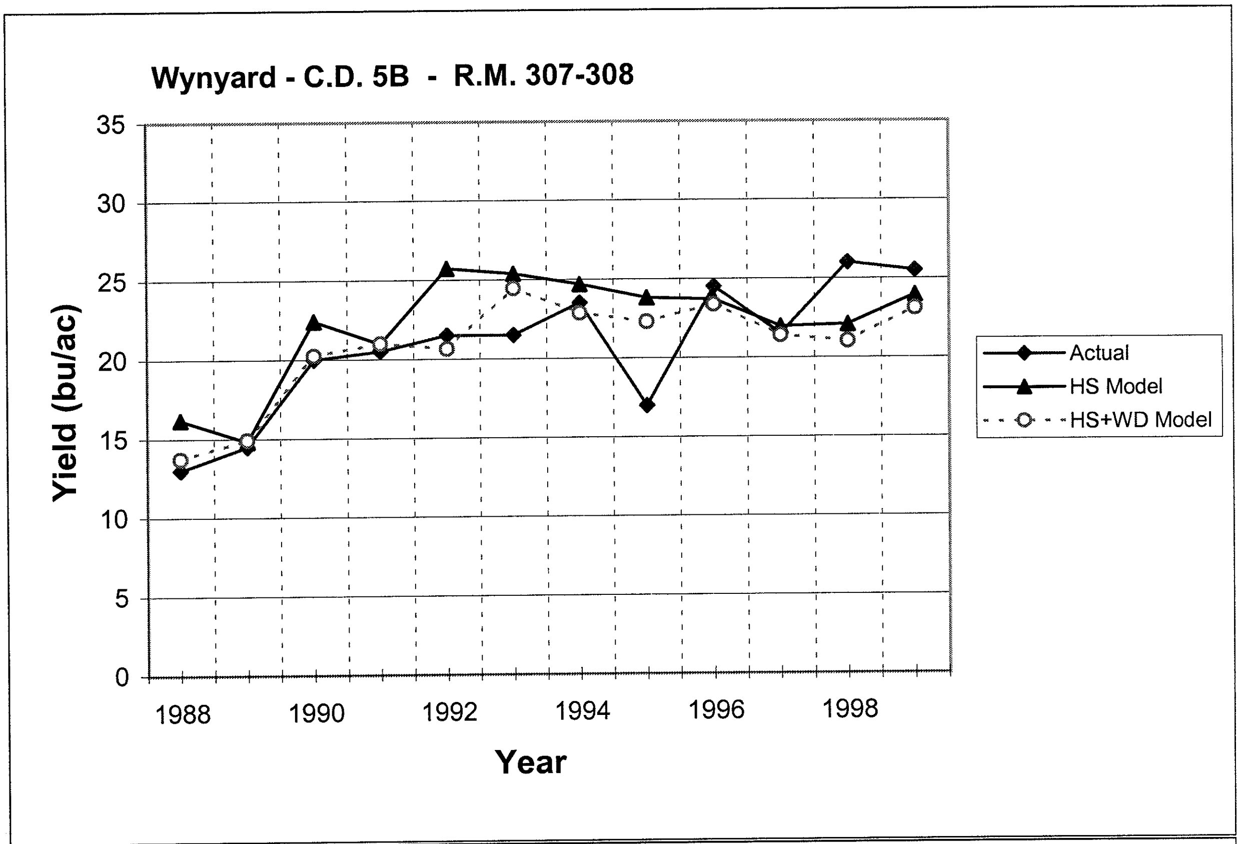

b) Actual and modeled yields - Wynyard - C.D. 5B - R.M. 307-308
Yield (bu/ac)
Year
Modeled
Actual

Figure 23. Comparison of actual yields with estimated yields from a heat stress (HS) and combined heat stress and water deficit (HS+WD) model in the Wynyard and North Battleford areas.



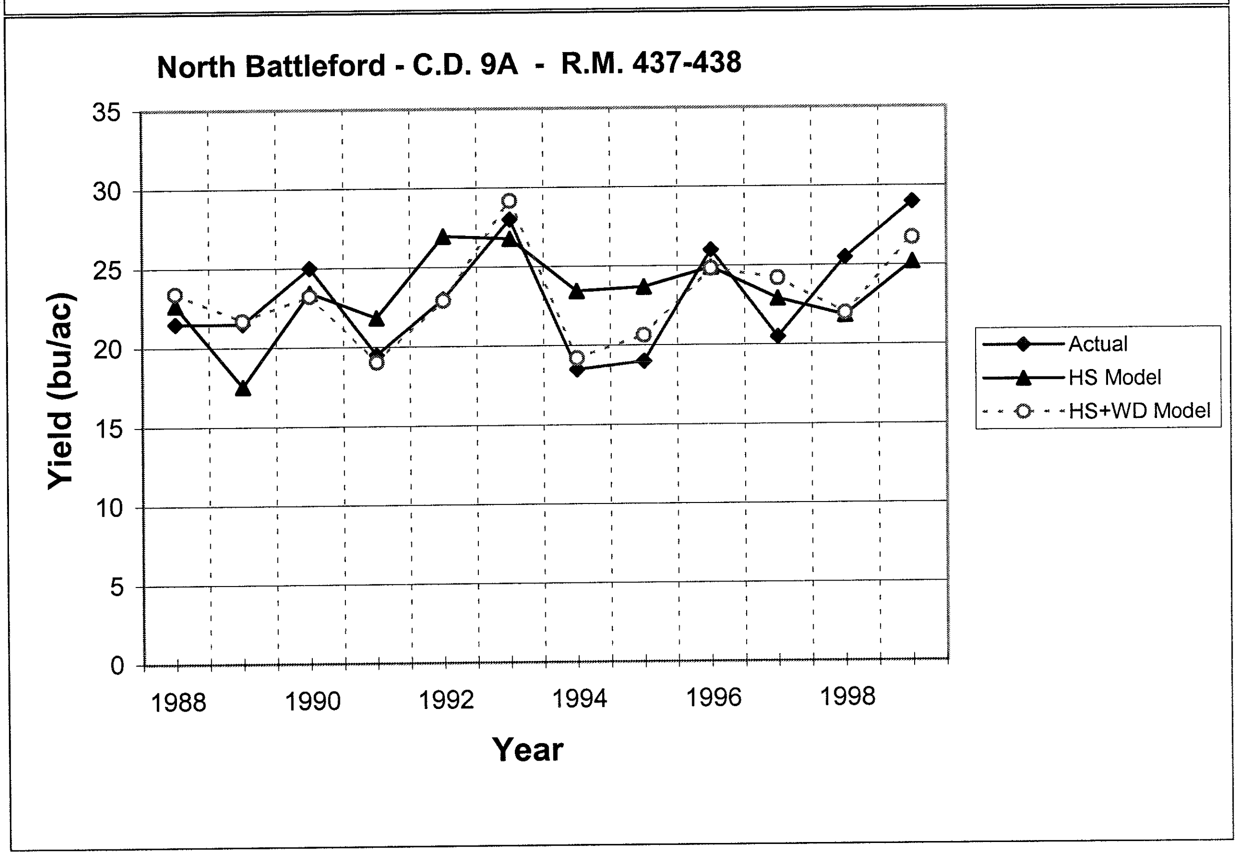


Figure 24. Average canola yields from 1984 to 1999 in main canola growing crop districts of Saskatchewan.

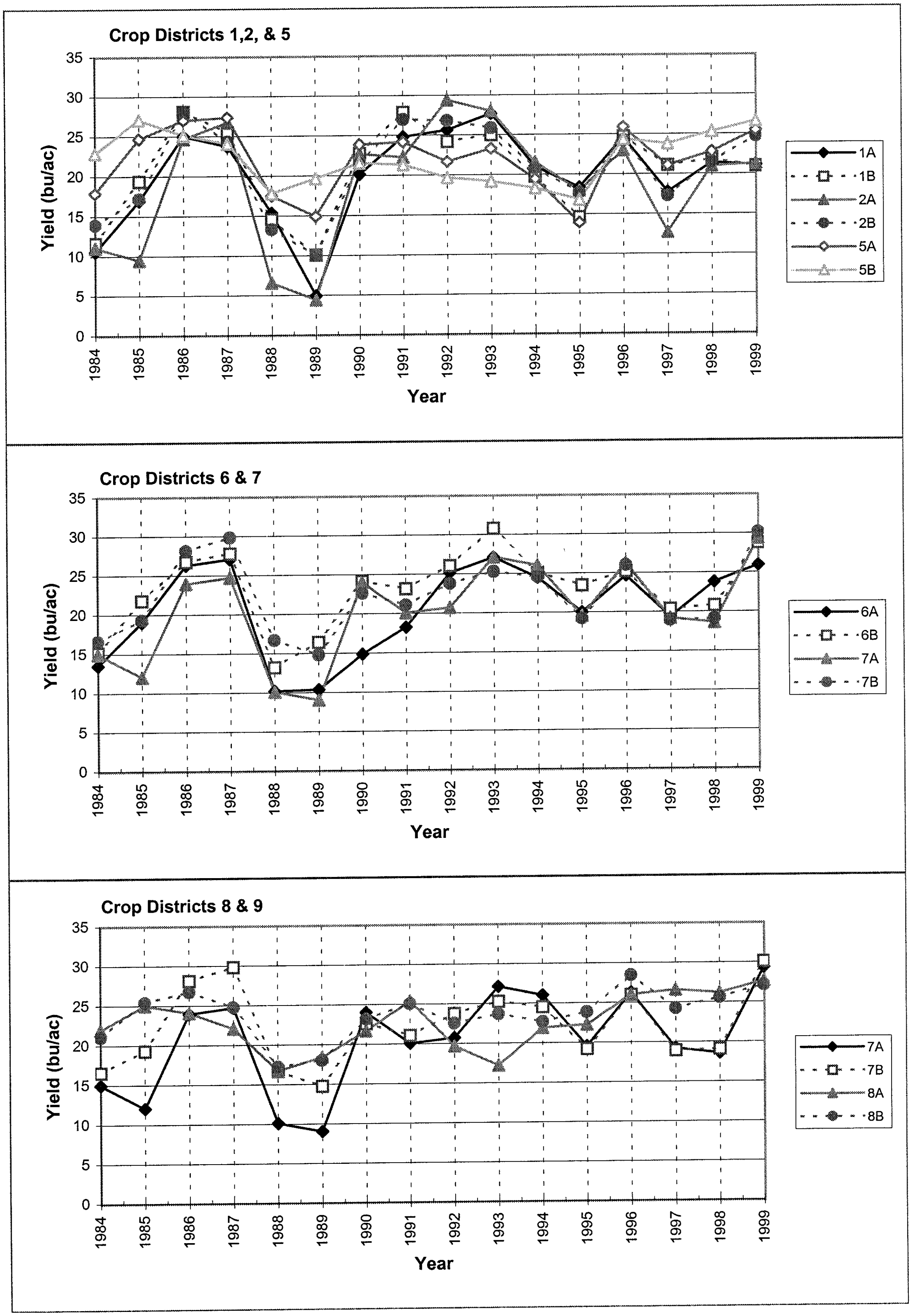
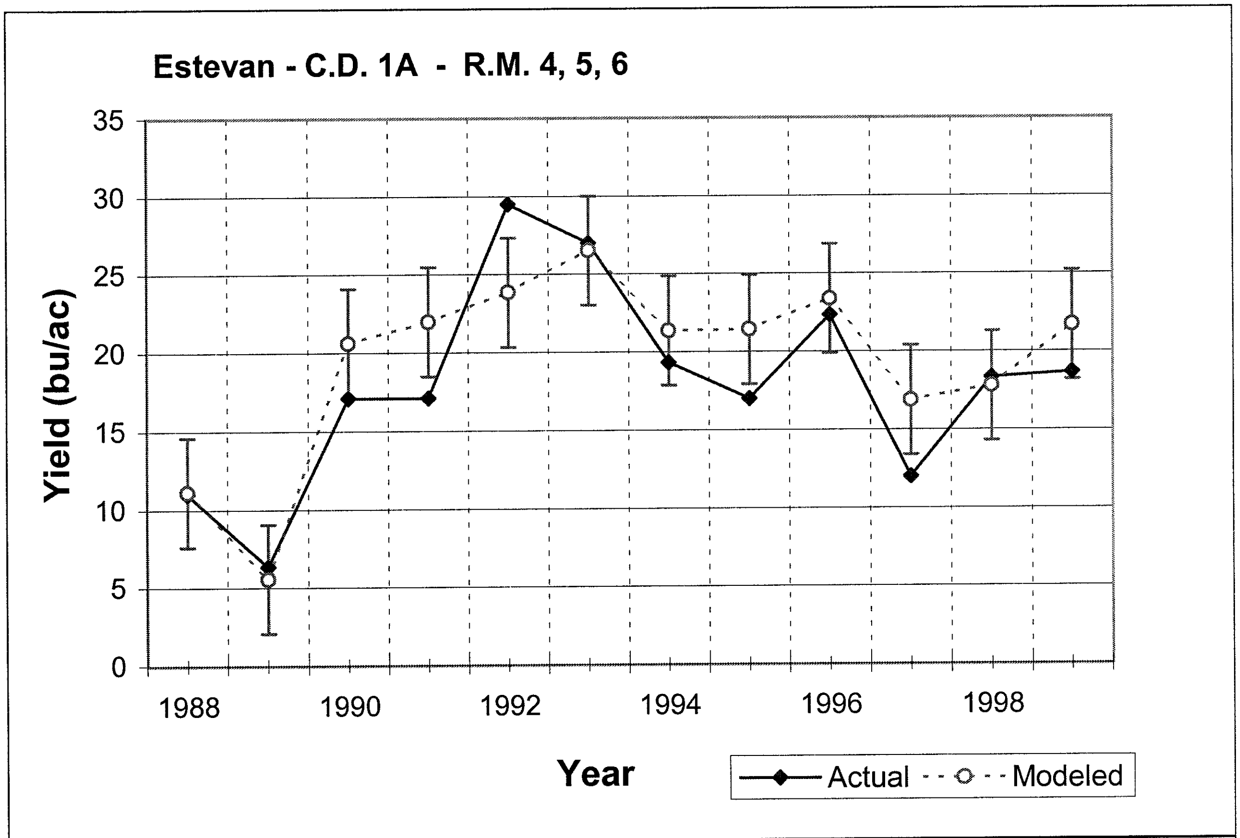


Figure 25. Plot of actual and modeled canola yields for the 1988 to 1999 period in crop districts 1A and 1B..



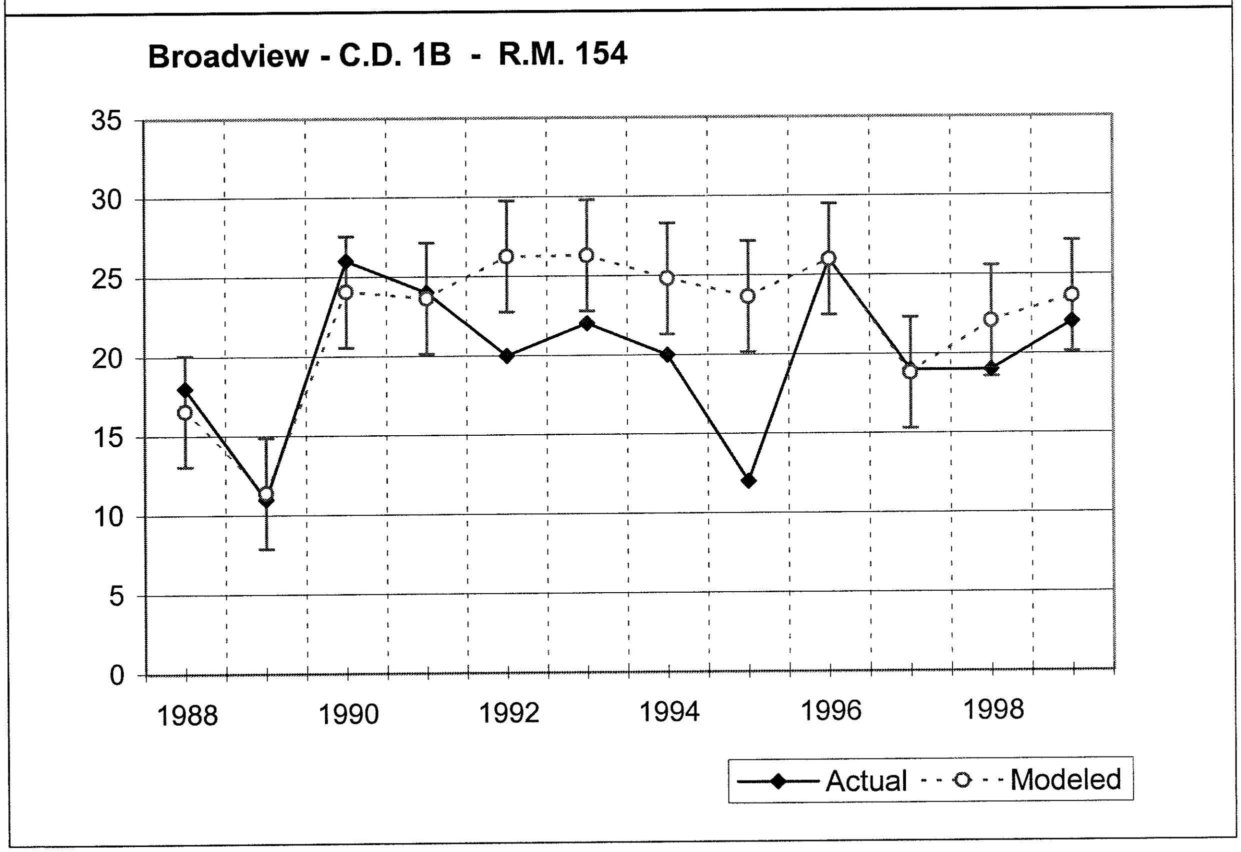
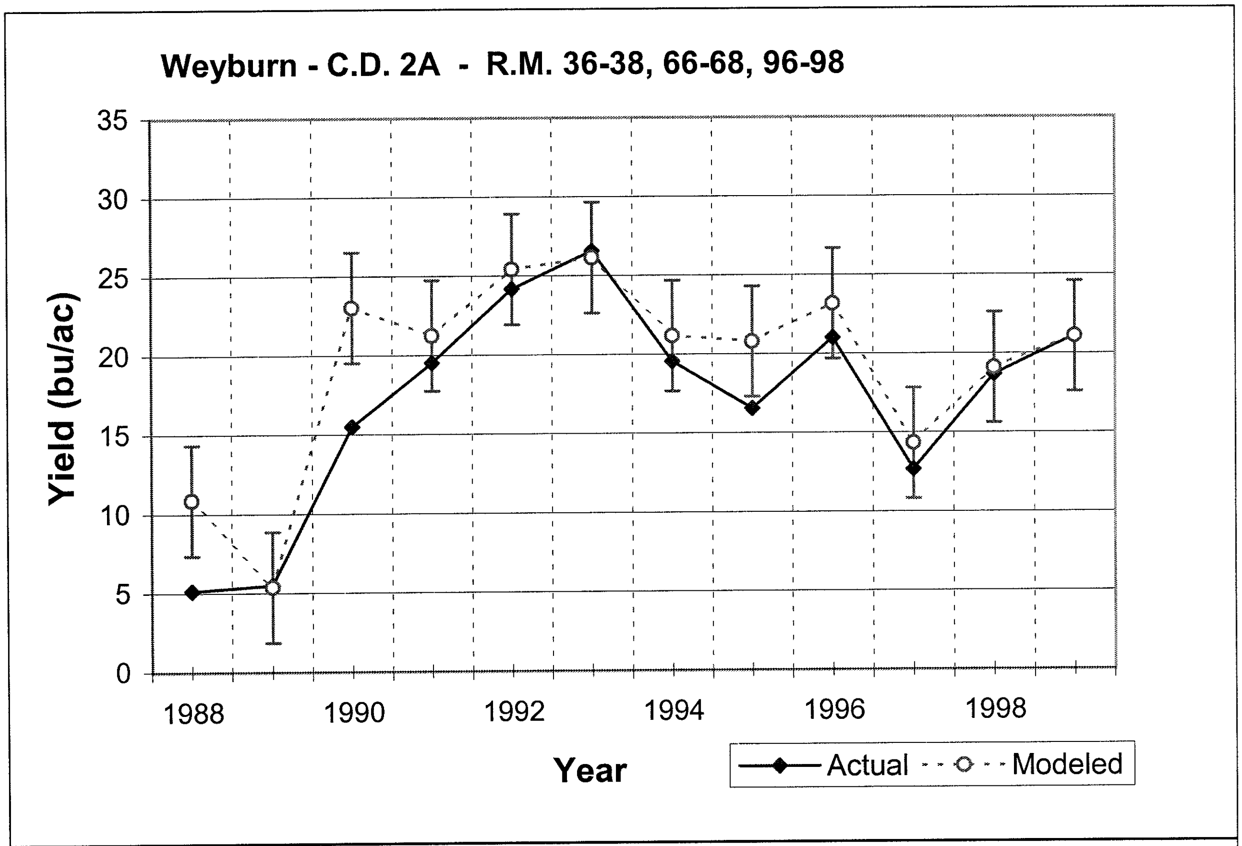


Figure 26. Plot of actual and modeled canola yields for the 1988 to 1999 period in crop districts 2A and 2B.



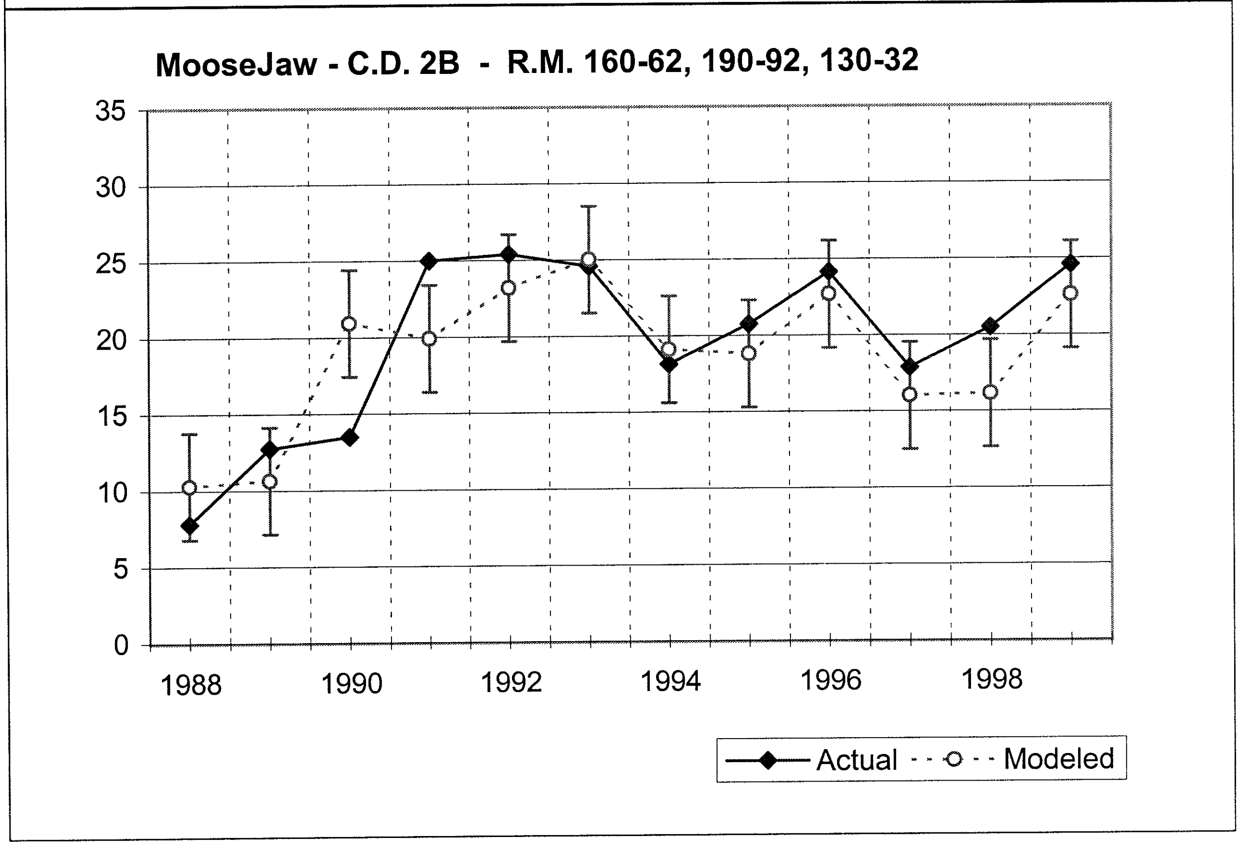
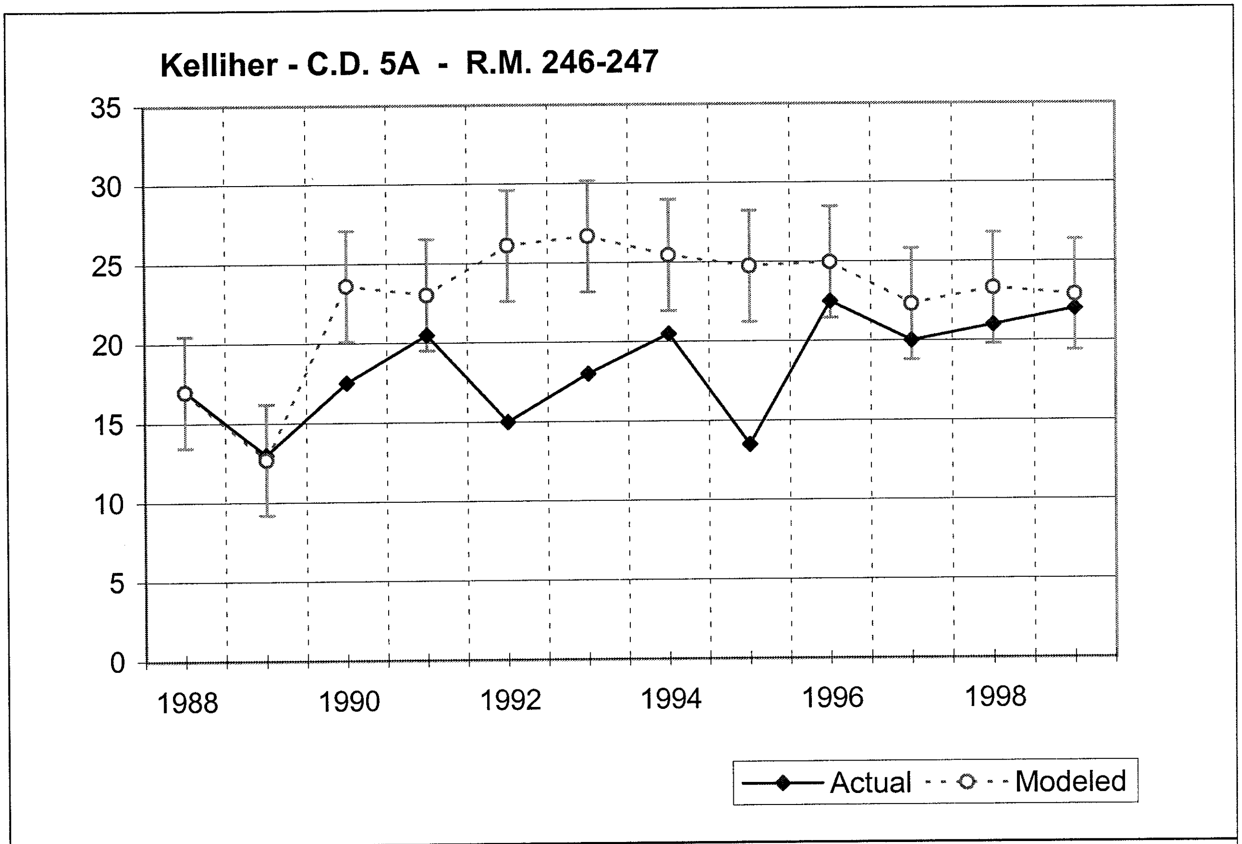


Figure 27. Plot of actual and modeled canola yields for the 1988 to 1999 period in crop districts 5A and 5B.



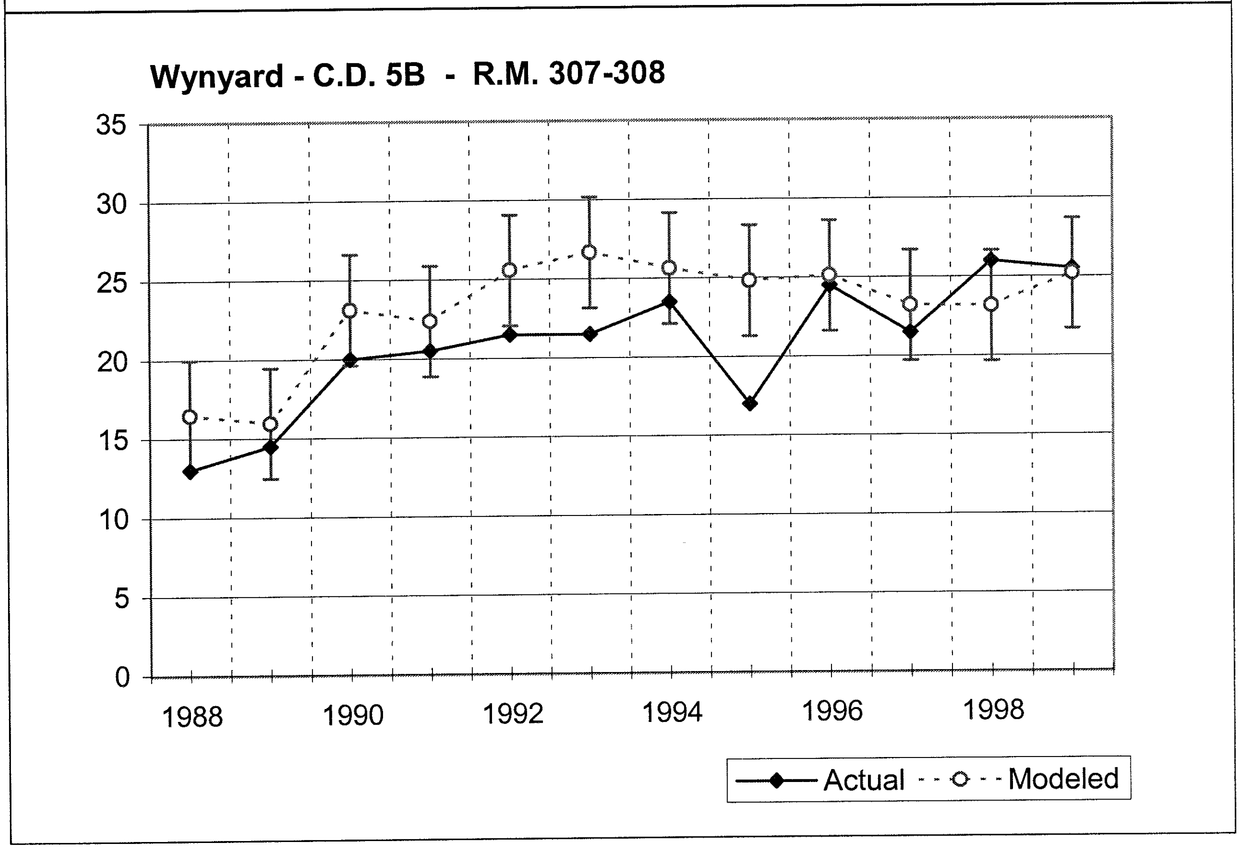
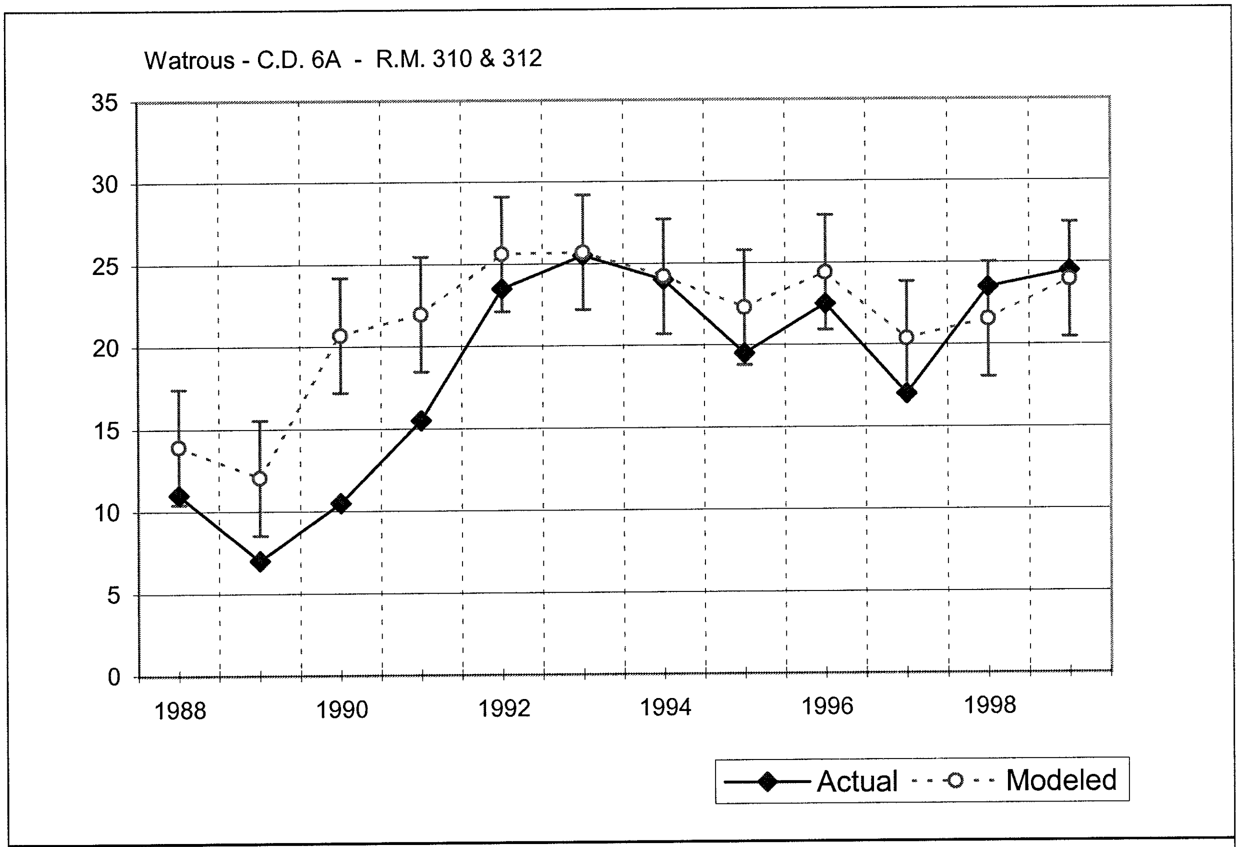


Figure 28. Plot of actual and modeled canola yields for the 1988 to 1999 period in crop districts 6A and 6B.



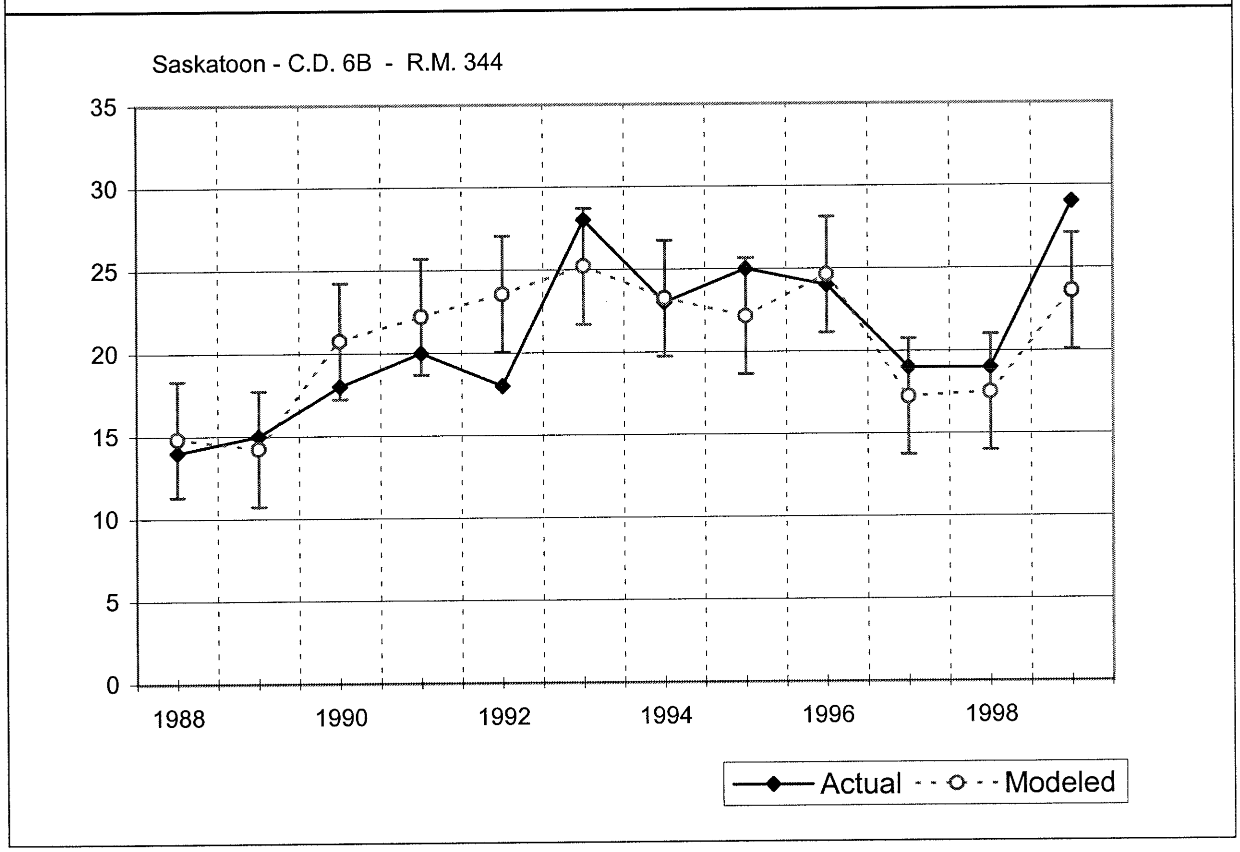
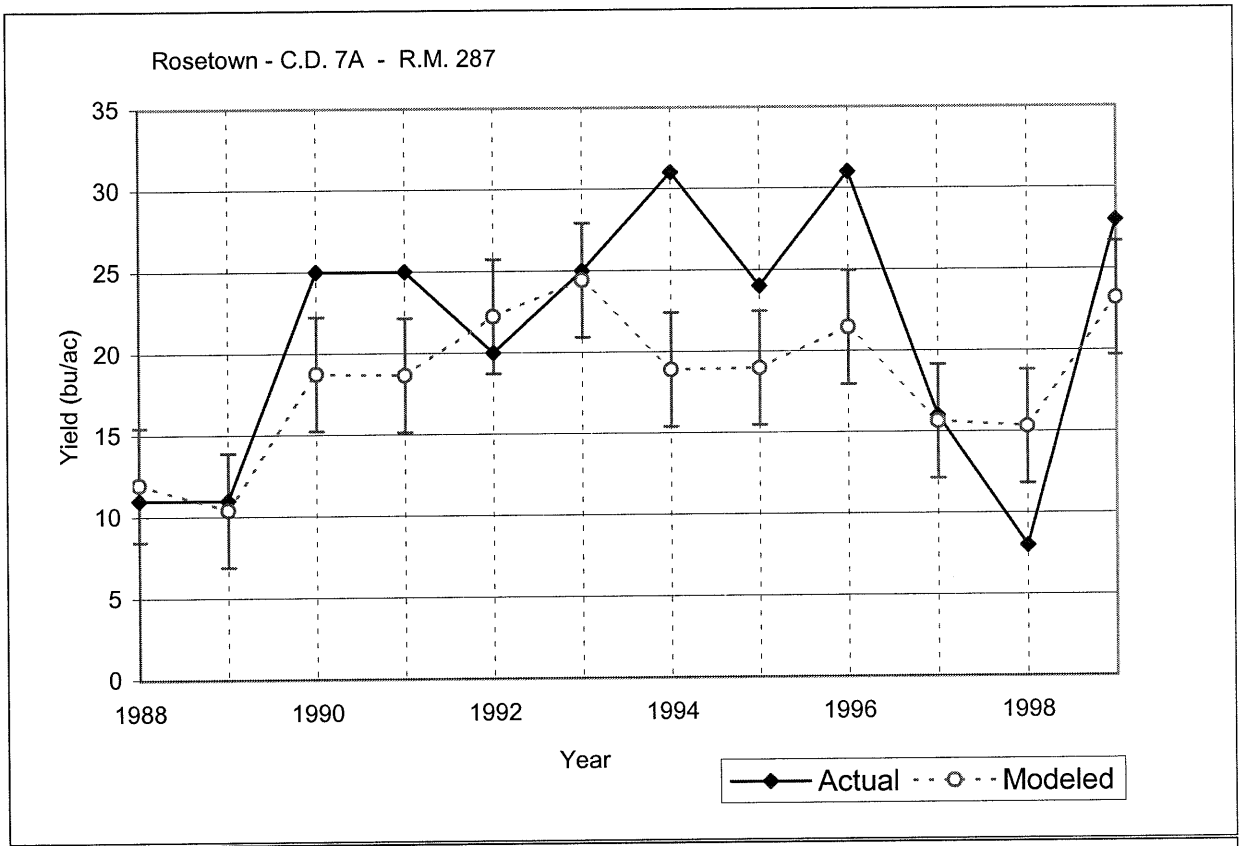


Figure 29. Plot of actual and modeled canola yields for the 1988 to 1999 period in crop districts 7A and 7B.



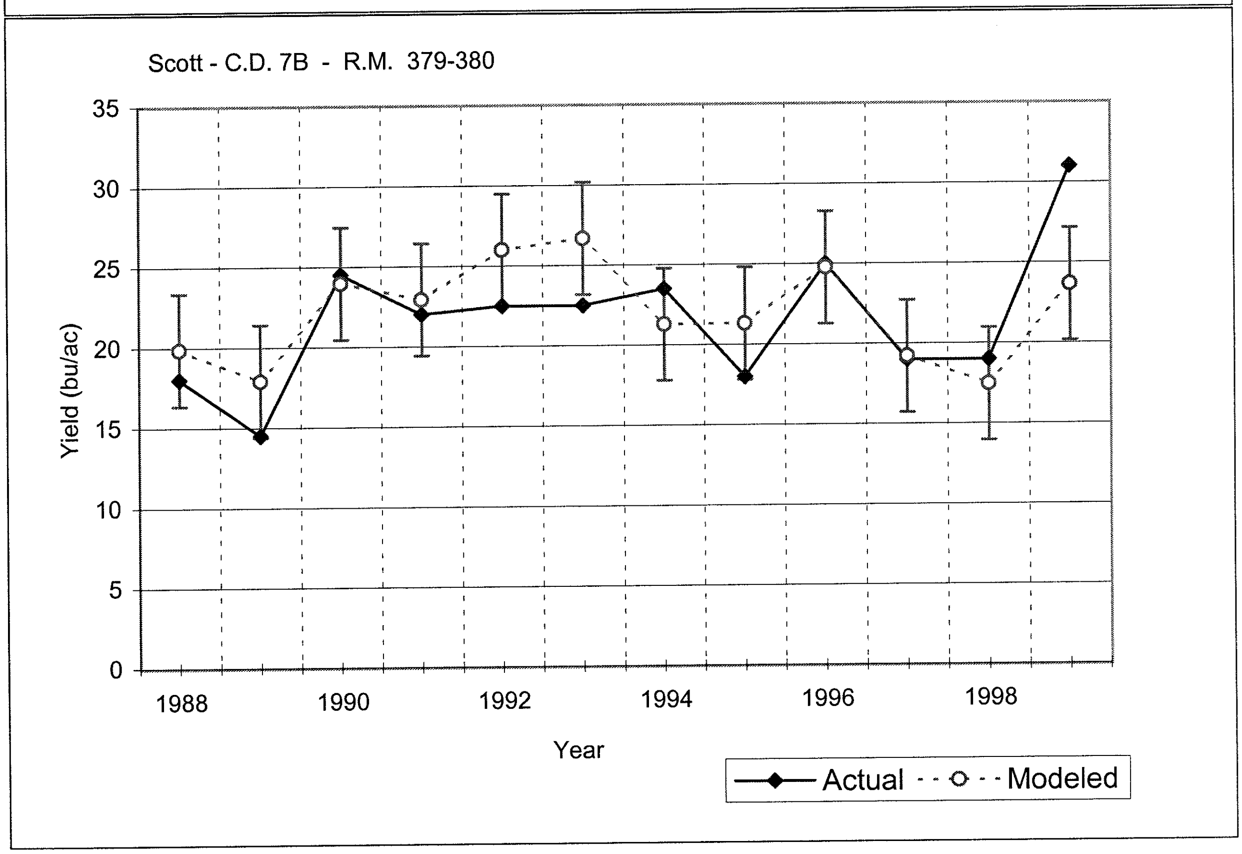


Figure 30. Plot of actual and modeled canola yields for the 1988 to 1999 period in crop districts 8A and 8B.

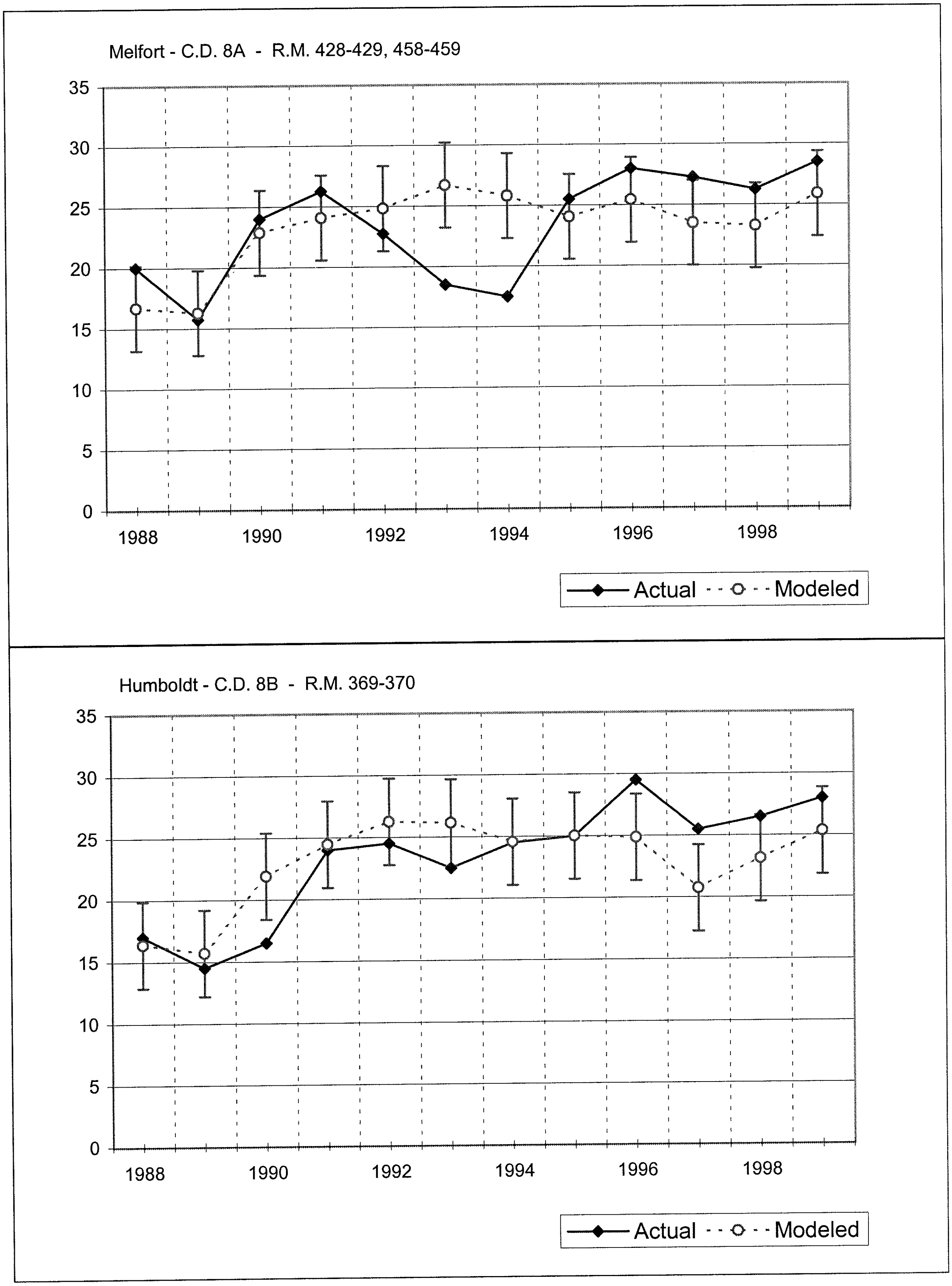


Figure 31. Plot of actual and modeled canola yields for the 1988 to 1999 period in crop districts 9A and 9B.

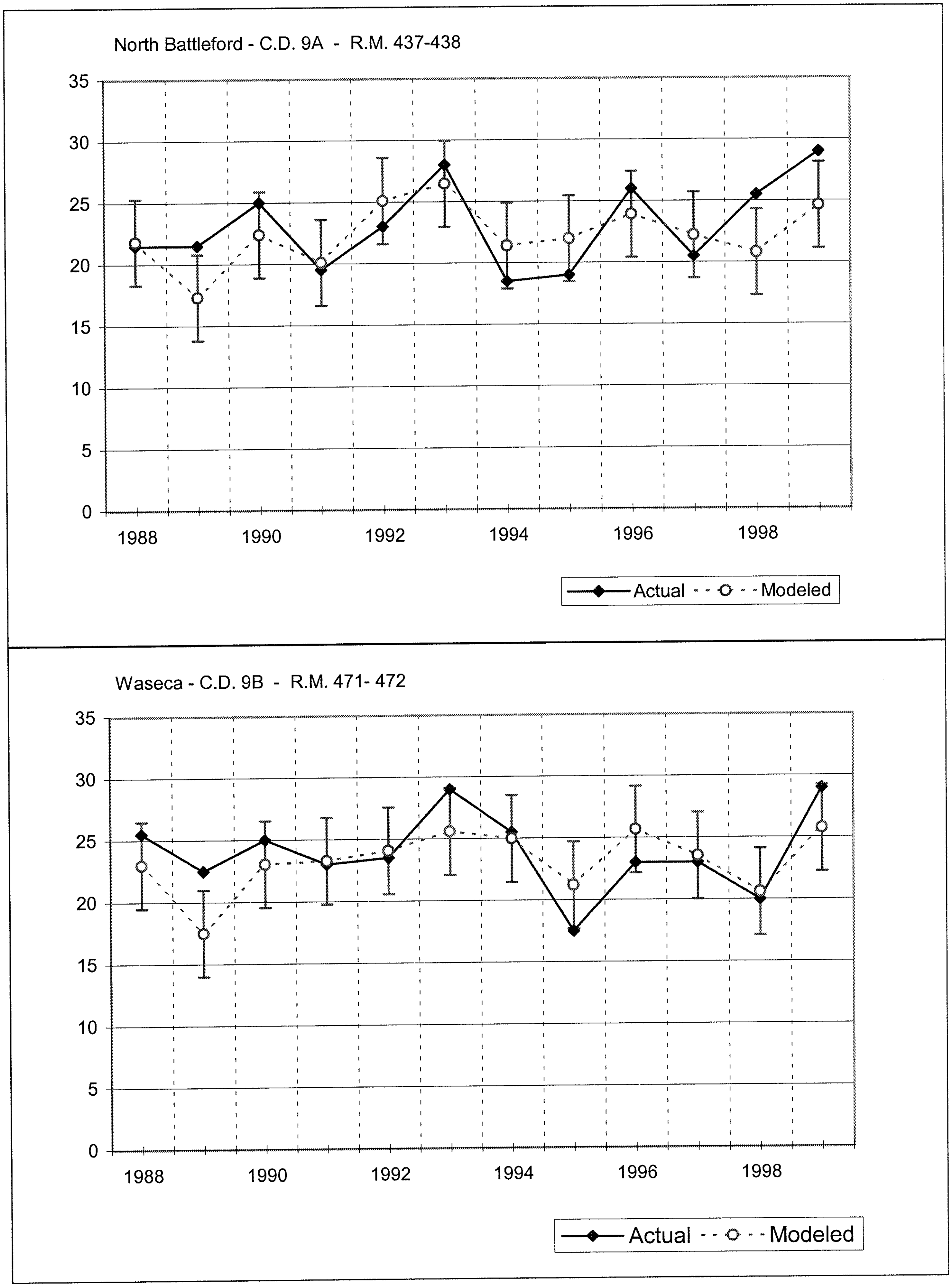
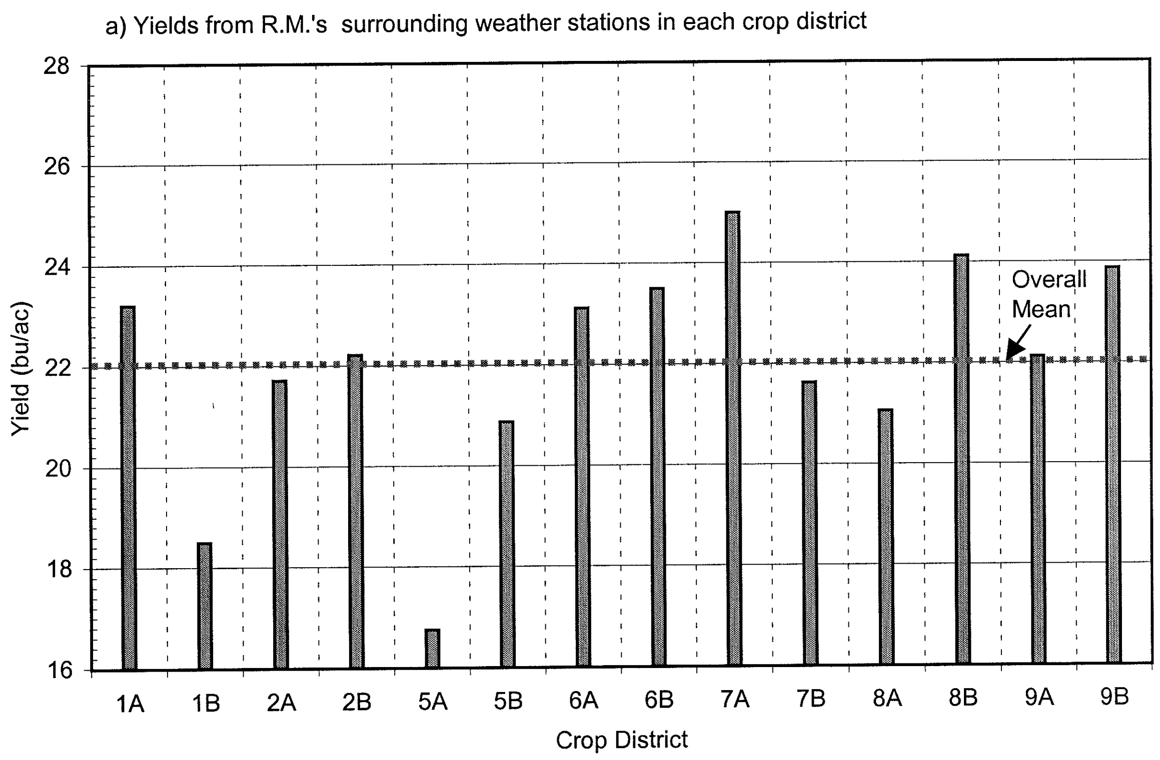


Figure 32. Average canola yields from 1992 to 1995: a) yields from rural municipalities surrounding weather stations, and b) average yields for the entire crop districts.



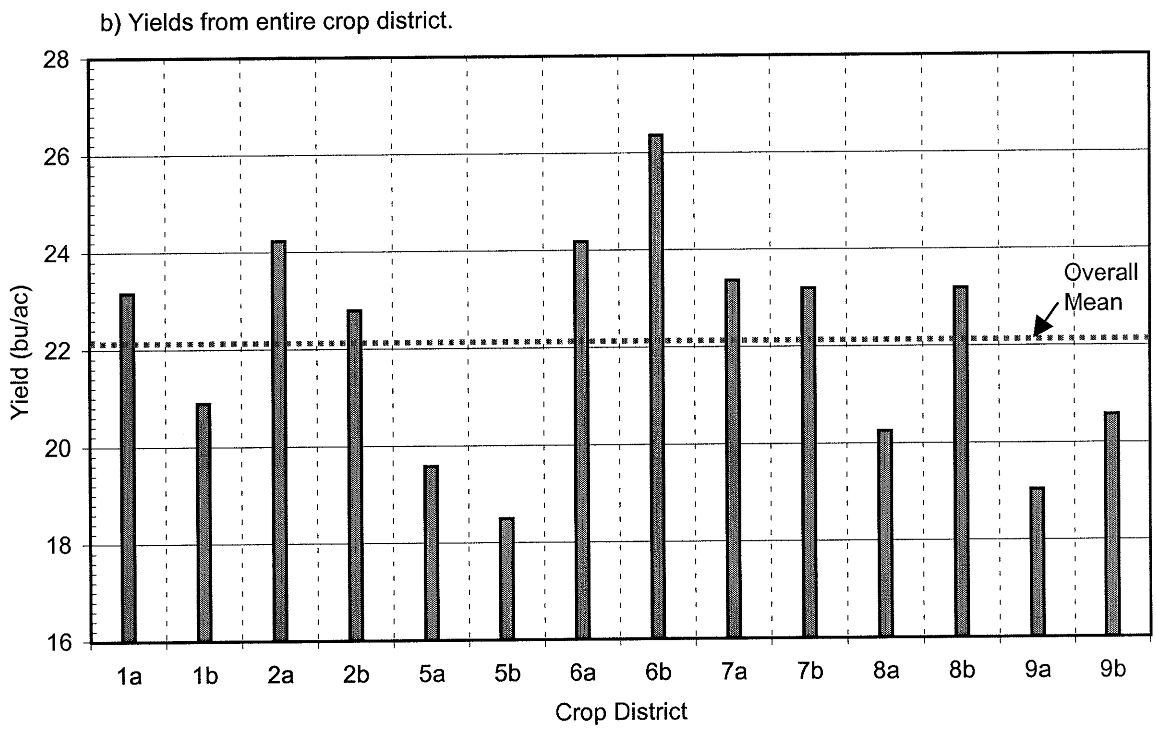


Table 1. Summary of factors suspected of causing reduced canola yields in Saskatchewan, 1994 & 1995

Factor	Possible yield loss	Small yield loss	Substantial yield loss	Aggregate score *
High temp at flowering/ early seed set	29	22	8	97
Disease **	16	21	7	79
Insect damage	21	17	6	73
Excess water, flooding, waterlogging	21	14	4	61
Perennial weeds	28	14	1	59
Poor early crop vigor	17	10	7	58
Annual weeds	30	8	3	55
General poor growth	19	11	4	53
Poor crop establishment	11	9	7	50
Soil conditions (excluding fertility)	25	6	0	37
Inadequate fertility	19	3	1	28
Pesticide damage	8	0	1	11
Frost or cold damage	6	0	0	6

* Aggregate score = Column 1 + (2 x column 2) + (3 x column3).

** Disease scoring based on interpretation of comments.

Source: Canola Guide, Dec 96 / Jan 97 by Stewart Brandt, AAFC, Scott, SK

Table 2. Coefficients of multiple regression equations of canola yields vs heat stress and water deficit for selected locations in Saskatchewan.

Crop District	Weather and yield location	Intercept (bu/ac)	July SDD coefficient (bu/ac)/oC-day	Water Deficit coefficient (bu/ac)/mm	Goodness of fit (R2)
1A	Estevan	24.5	-0.021	-0.089	0.97
1B	Broadview	27.3	-0.108	-0.021	0.90
2A	Weyburn	24.5	-0.109	-0.014	0.83
2B	MooseJaw	26.9	-0.046	-0.069	0.75
5A	Kelliher	23.7	-0.066	-0.024	0.79
5B	Wynyard	28.5	-0.115	-0.051	0.88
6A	Watrous	25.4	-0.099	-0.046	0.69
6B	Saskatoon	28.4	-0.125	-0.015	0.71
7A	Rosetown	39.4	-0.158	-0.066	0.80
7B	Scott	26.2	-0.043	-0.030	0.77
8A	Melfort	29.5	-0.058	-0.033	0.93
8B	Humboldt	30.5	-0.152	-0.020	0.68
9A	North Battleford	31.2	-0.073	-0.058	0.52
9B	Waseca	27.2	-0.002	-0.045	0.42

Table 3. Summary of results comparing actual and modeled canola yields :

a) presence of significantly lower than expected yields and
b) precipitation trend (% above (+) or below (-) normal) in year of significant difference.

a) Significant differences:

Crop District	1992	1993	1994	1995
1A				**
1B	**	**	**	**
2A				**
2B				
5A	**	**	**	**
5B	**	**		**
6A				
6B	**			
7A				
7B	**	**		
8A		**	**	
8B		**		
9A				
9B				**

** Actual yield significantly lower than modeled yield

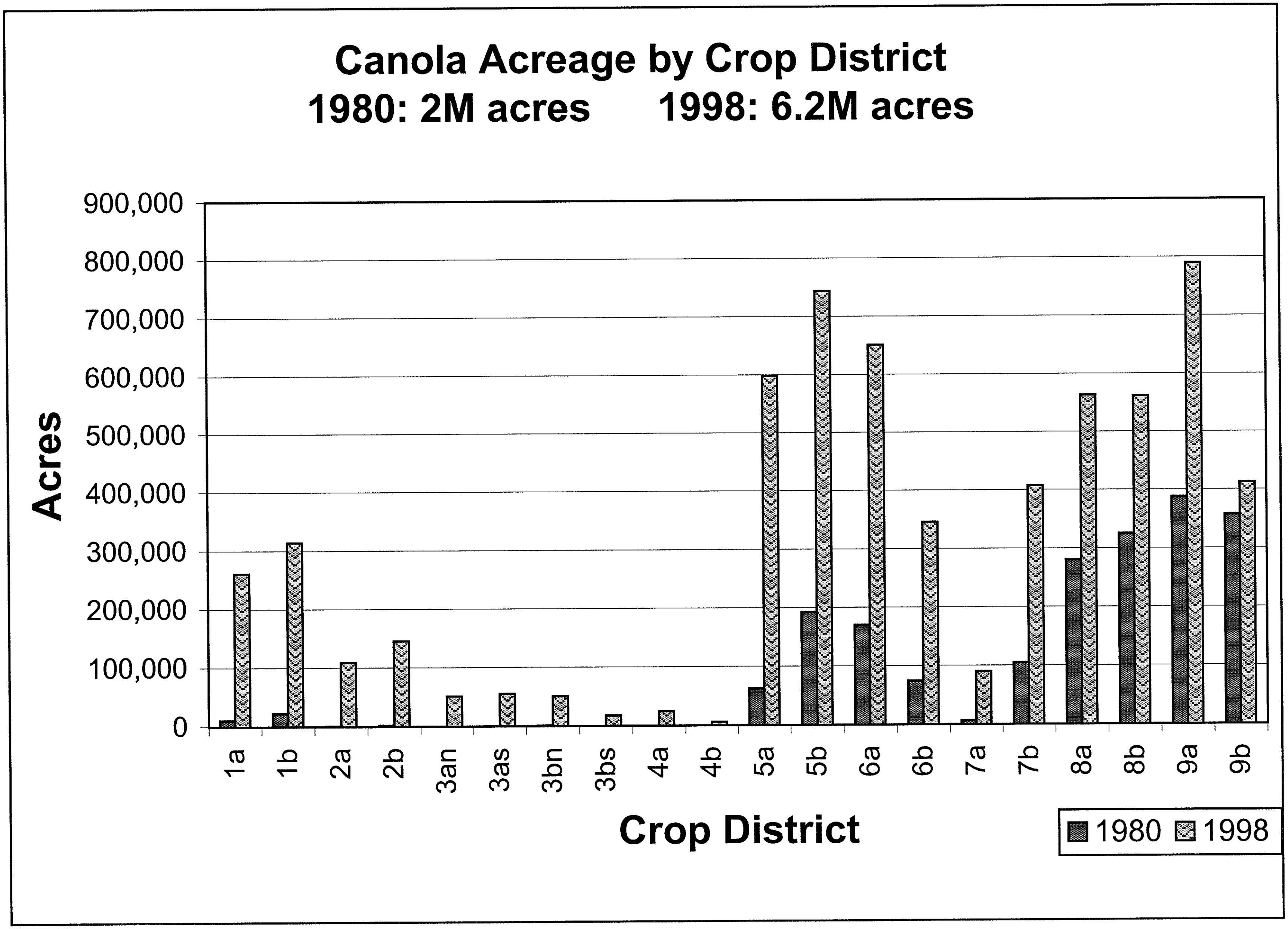
b) Precipitation[1] trends.

Crop District	1992	1993	1994	1995
1A				-5.1%
1B	-10.1%	15.1%	27.9%	28.1%
2A				19.1%
2B				
5A	-13.0%	28.1%	26.9%	30.1%
5B	-32.8%	52.5%		53.8%
6A				
6B	-15.9%			
7A				
7B	10.0%	12.3%		
8A		45.9%	3.5%	
8B		46.6%		
9A				
9B				-23.9%

1. Precipitation from May to August incl.

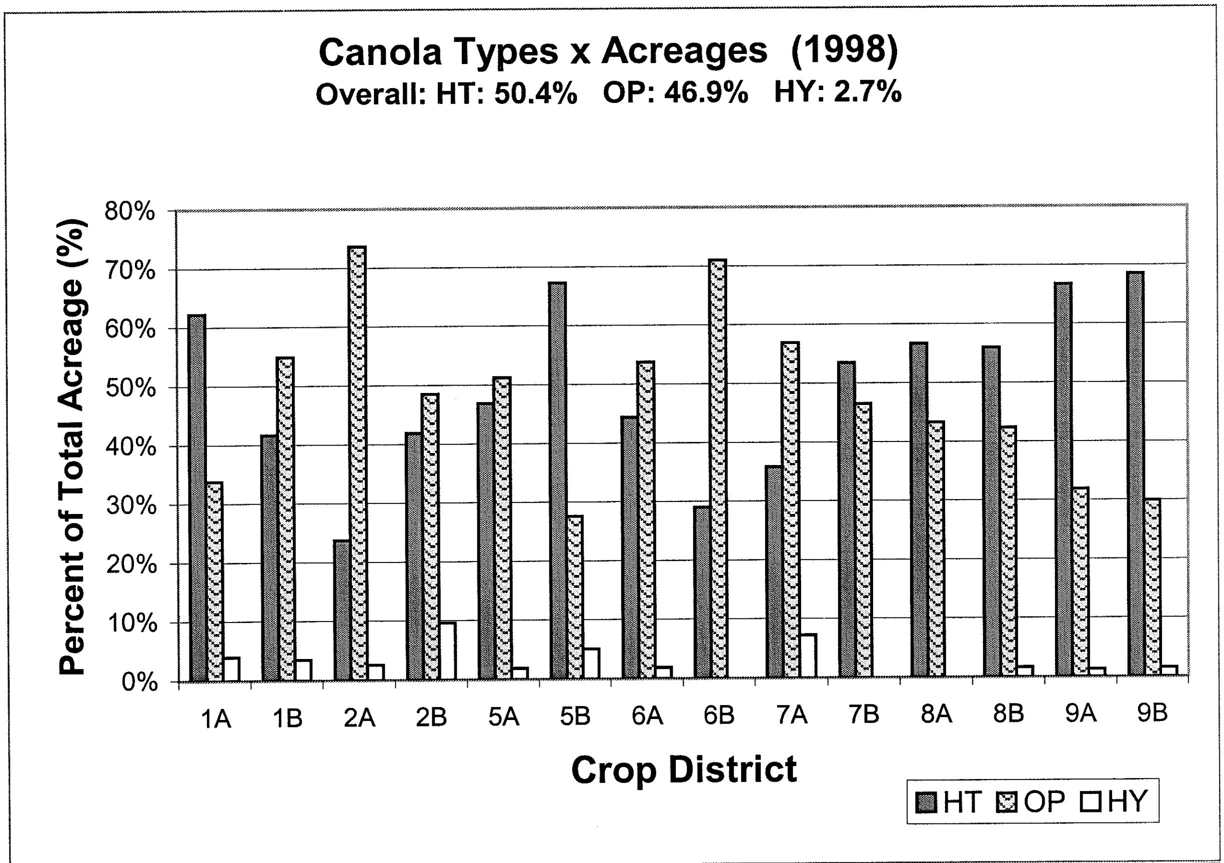
APPENDIX

Figure A1.



Canola Acreage by Crop District
1980: 2M acres 1998: 6.2M acres
Acres
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
1a
1b
2a
2b
3an
3as
3bn
3bs
4a
4b
5a
5b
6a
6b
7a
7b
8a
8b
9a
9b
Crop District
1980
1998

Figure A2.


Canola Types x Acreages (1998)
Overall: HT: 50.4% OP: 46.9% HY: 2.7%
Percent of Total Acreage (%)
80%
70%
60%
50%
40%
30%
20%
10%
0%
1A 1B 2A 2B 5A 5B 6A 6B 7A 7B 8A 8B 9A 9B
Crop District
HT OP HY

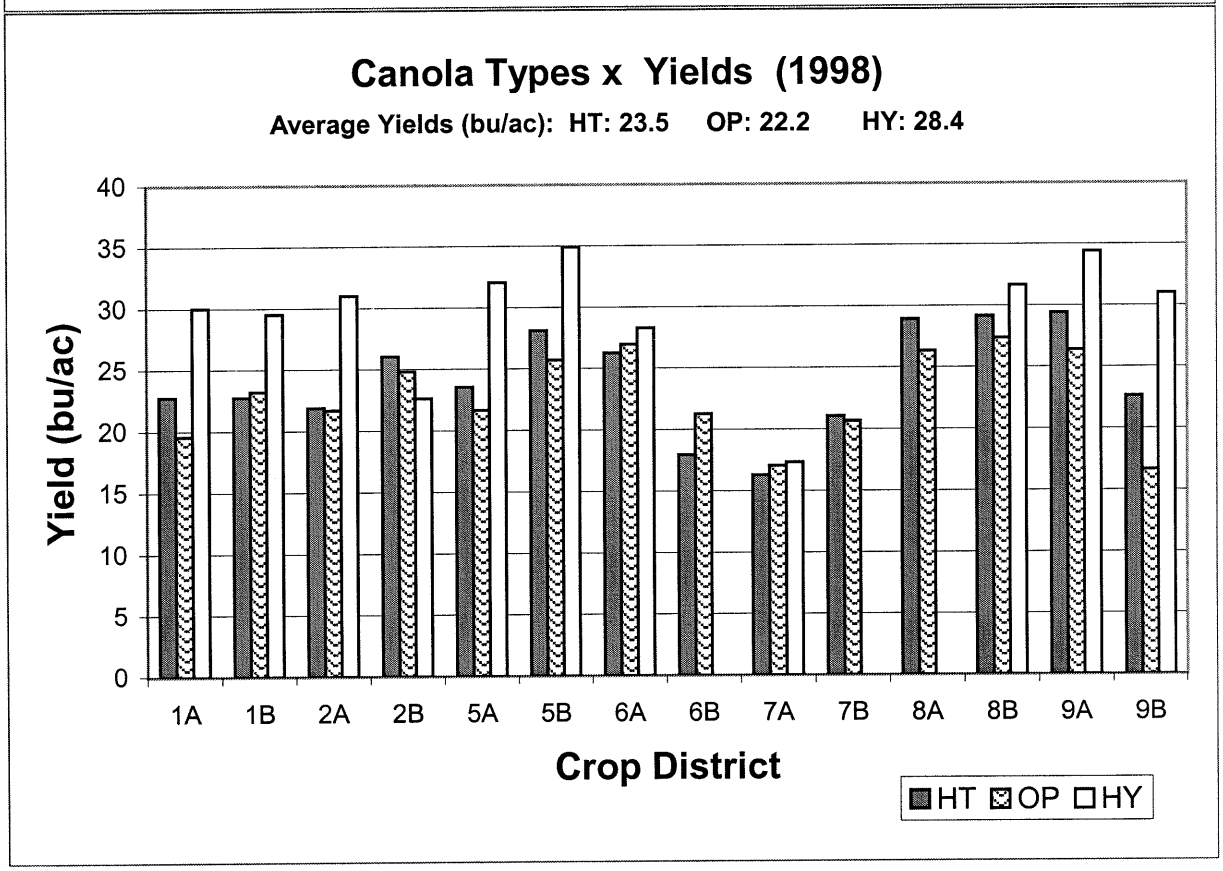
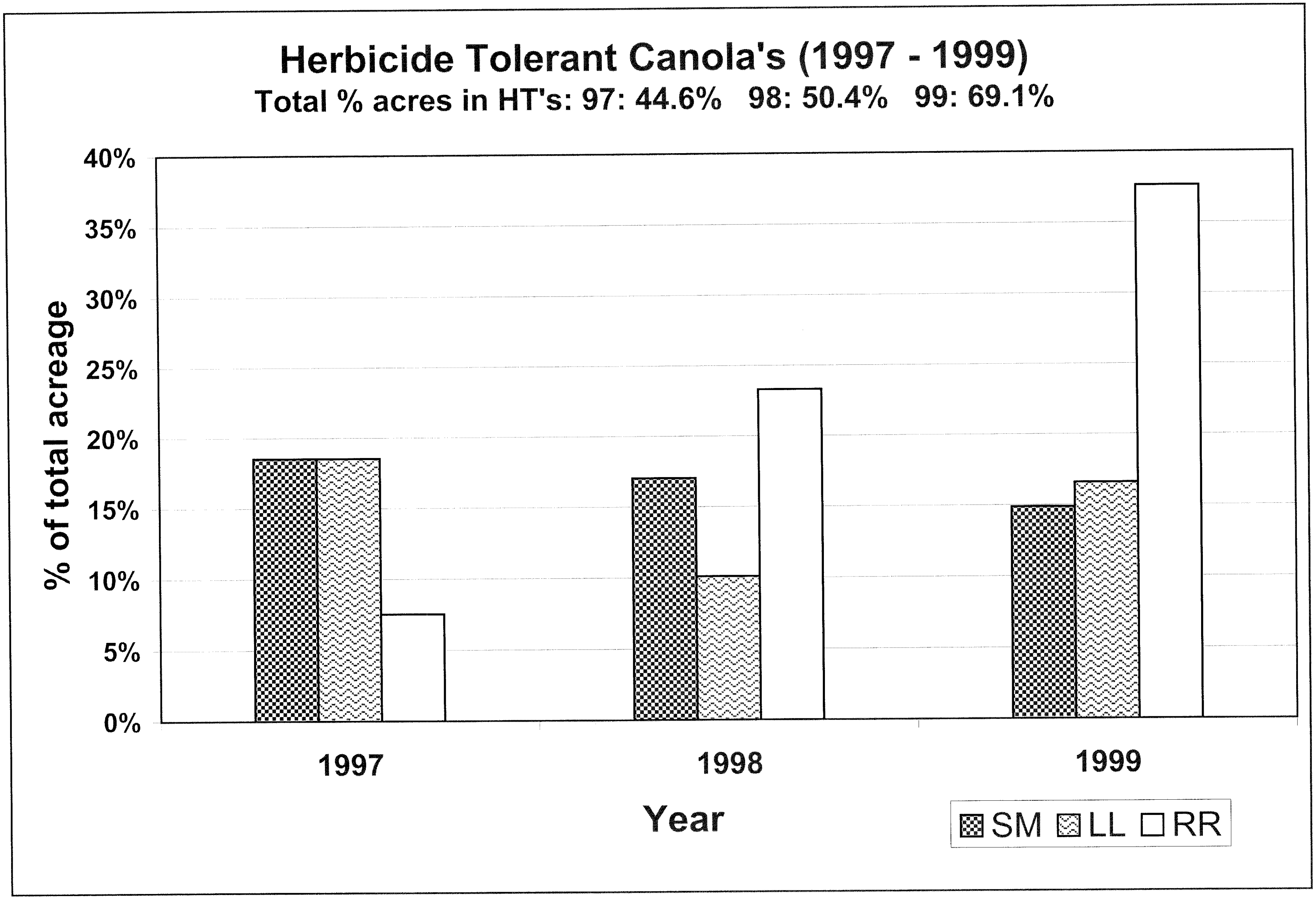
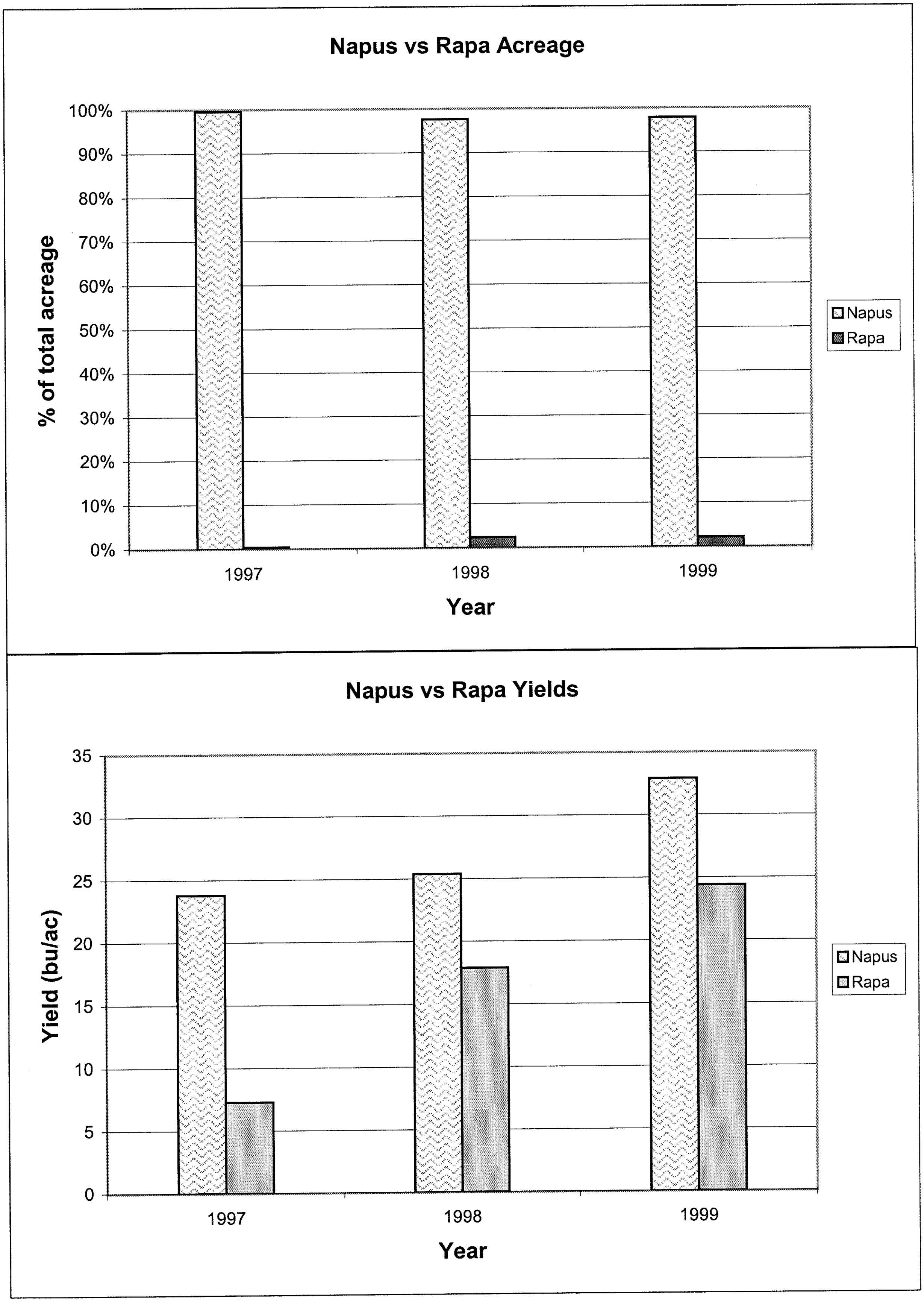

Canola Types x Yields (1998)
Average Yields (bu/ac): HT: 23.5 OP: 22.2 HY: 28.4
Yield (bu/ac)
40
35
30
25
20
15
10
5
0
1A 1B 2A 2B 5A 5B 6A 6B 7A 7B 8A 8B 9A 9B
Crop District
HT OP HY

Figure A3.



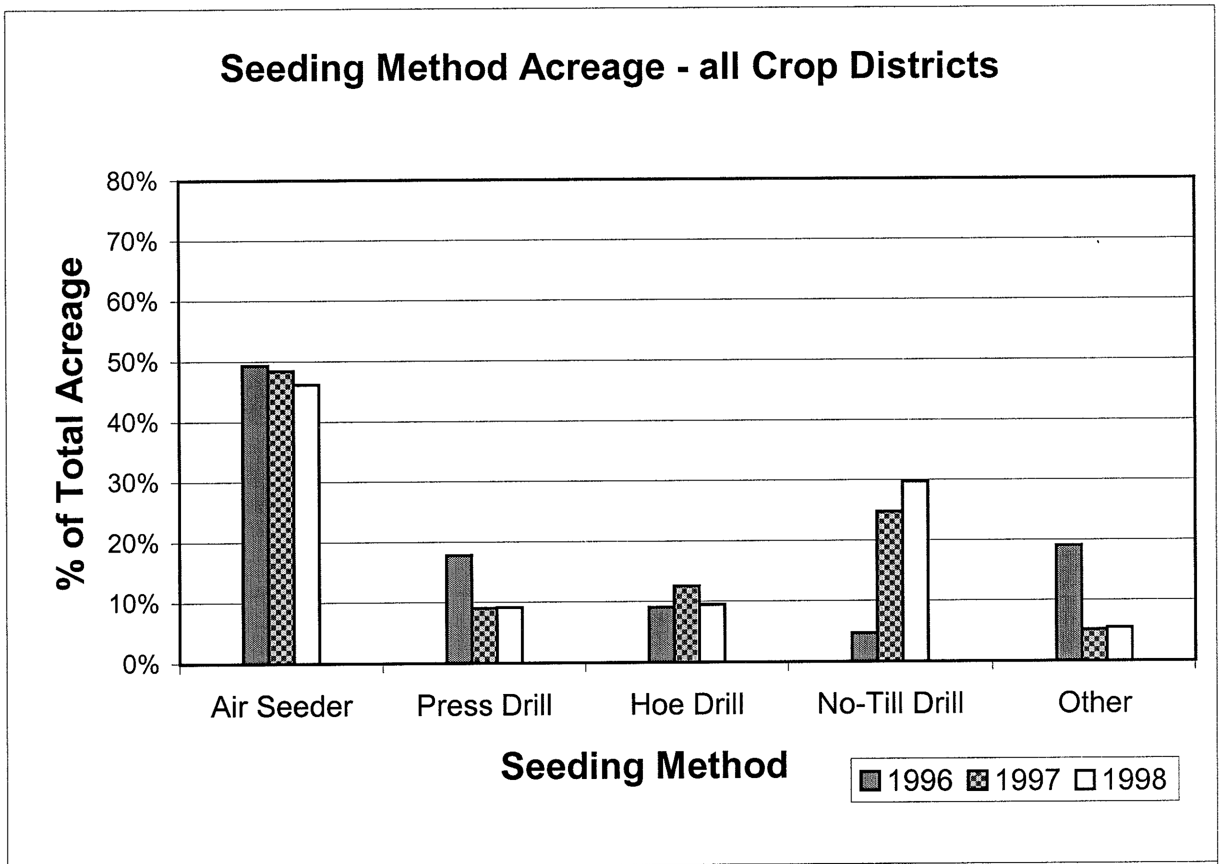
Herbicide Tolerant Canola's (1997 - 1999)
Total % acres in HT's: 97: 44.6% 98: 50.4% 99: 69.1%
% of total acreage
40%
35%
30%
25%
20%
15%
10%
5%
0%
1997
1998
1999
Year
SM
LL
RR

Figure A4.



Napus vs Rapa Acreage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% of total acreage
1997
1998
1999
Year
Napus
Rapa
Napus vs Rapa Yields
35
30
25
20
15
10
5
0
Yield (bu/ac)
1997
1998
1999
Year
Napus
Rapa

Figure A5.


Seeding Method Acreage - all Crop Districts
80%
70%
60%
50%
40%
30%
20%
10%
0%
% of Total Acreage
Air Seeder
Press Drill
Hoe Drill
No-Till Drill
Other
Seeding Method
1996
1997
1998

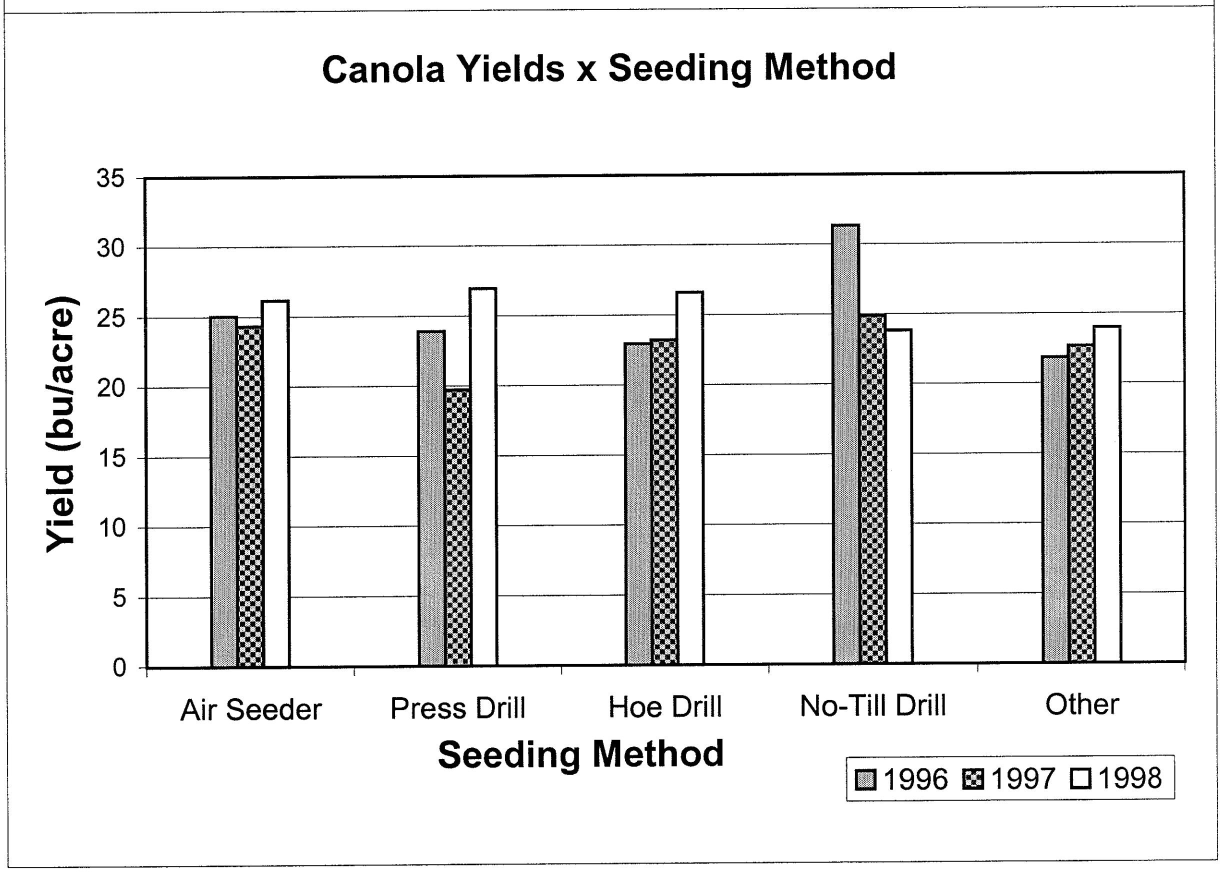
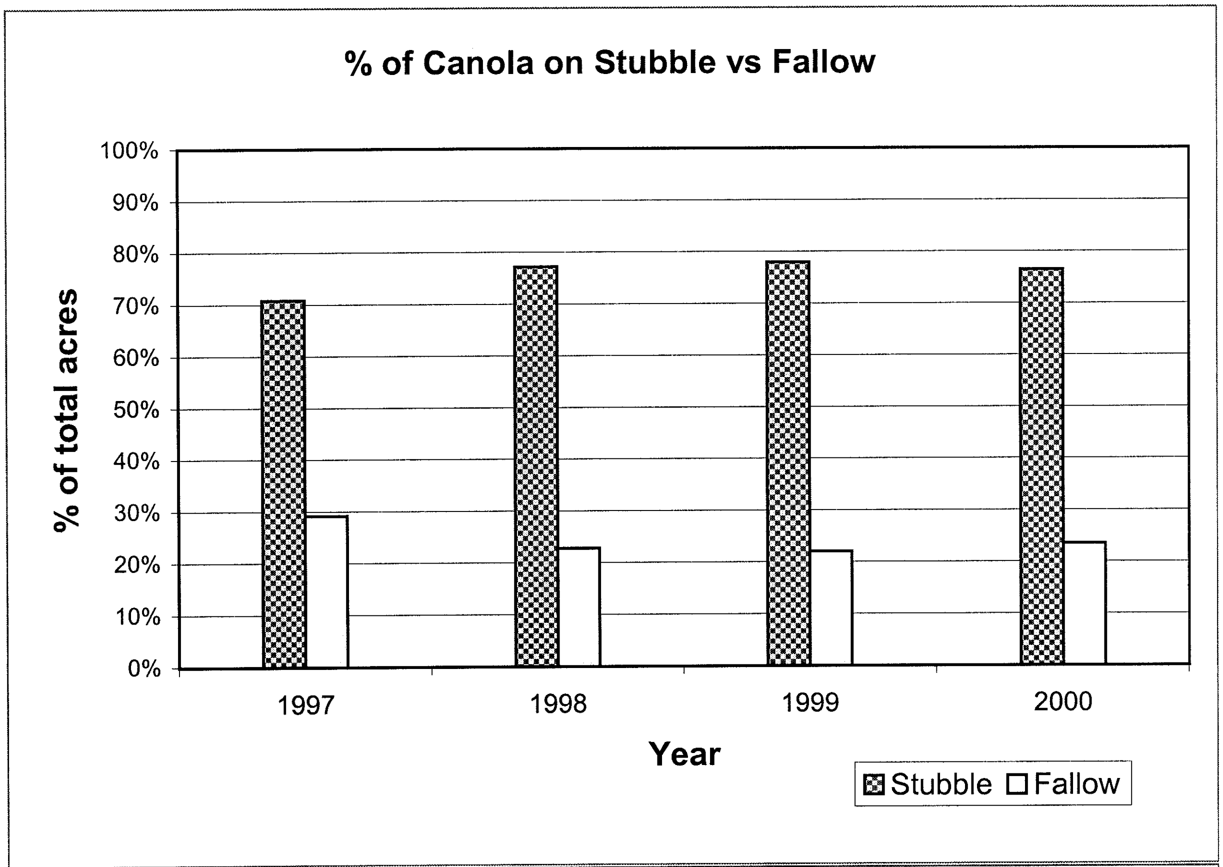

Canola Yields x Seeding Method
35
30
25
20
15
10
5
0
Yield (bu/acre)
Air Seeder
Press Drill
Hoe Drill
No-Till Drill
Other
Seeding Method
1996
1997
1998

Figure A6.


% of Canola on Stubble vs Fallow
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% of total acres
1997
1998
1999
2000
Year
Stubble
Fallow

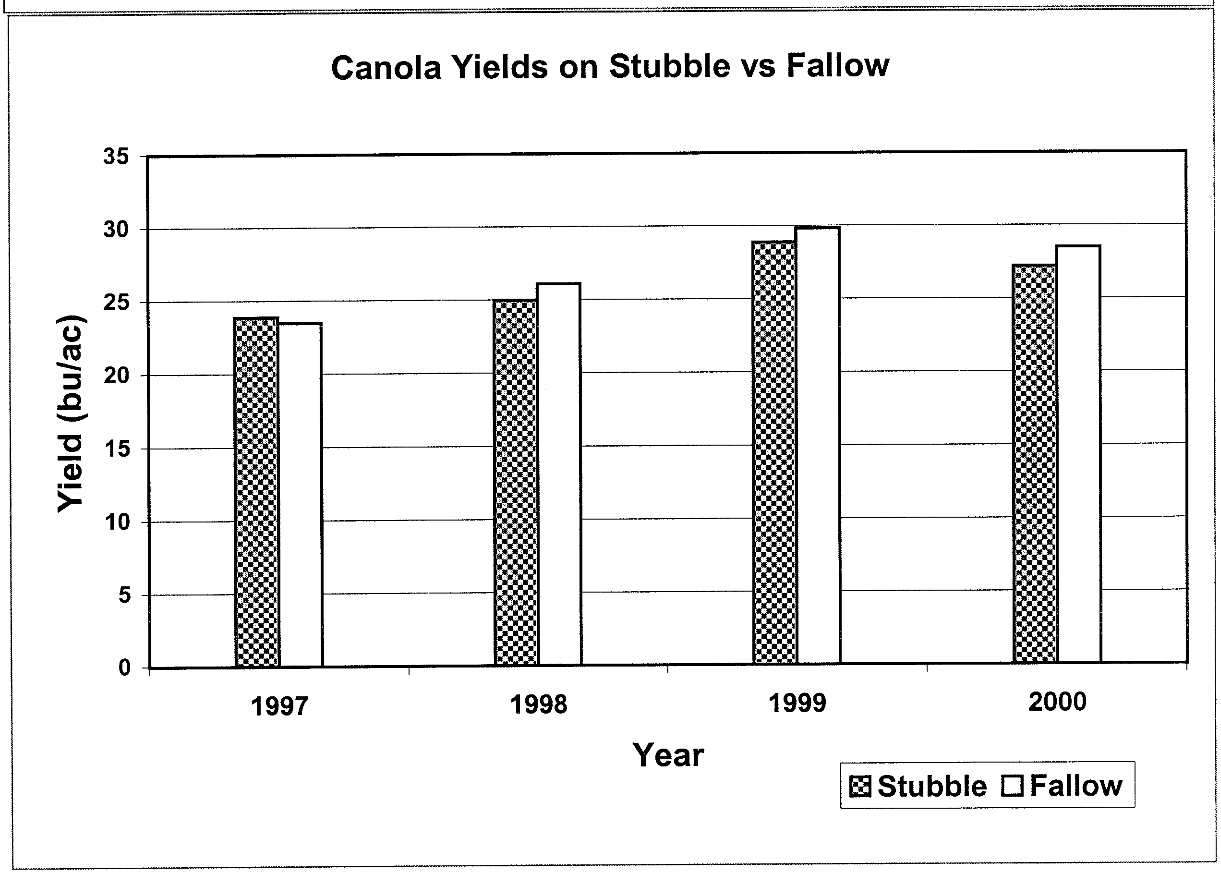
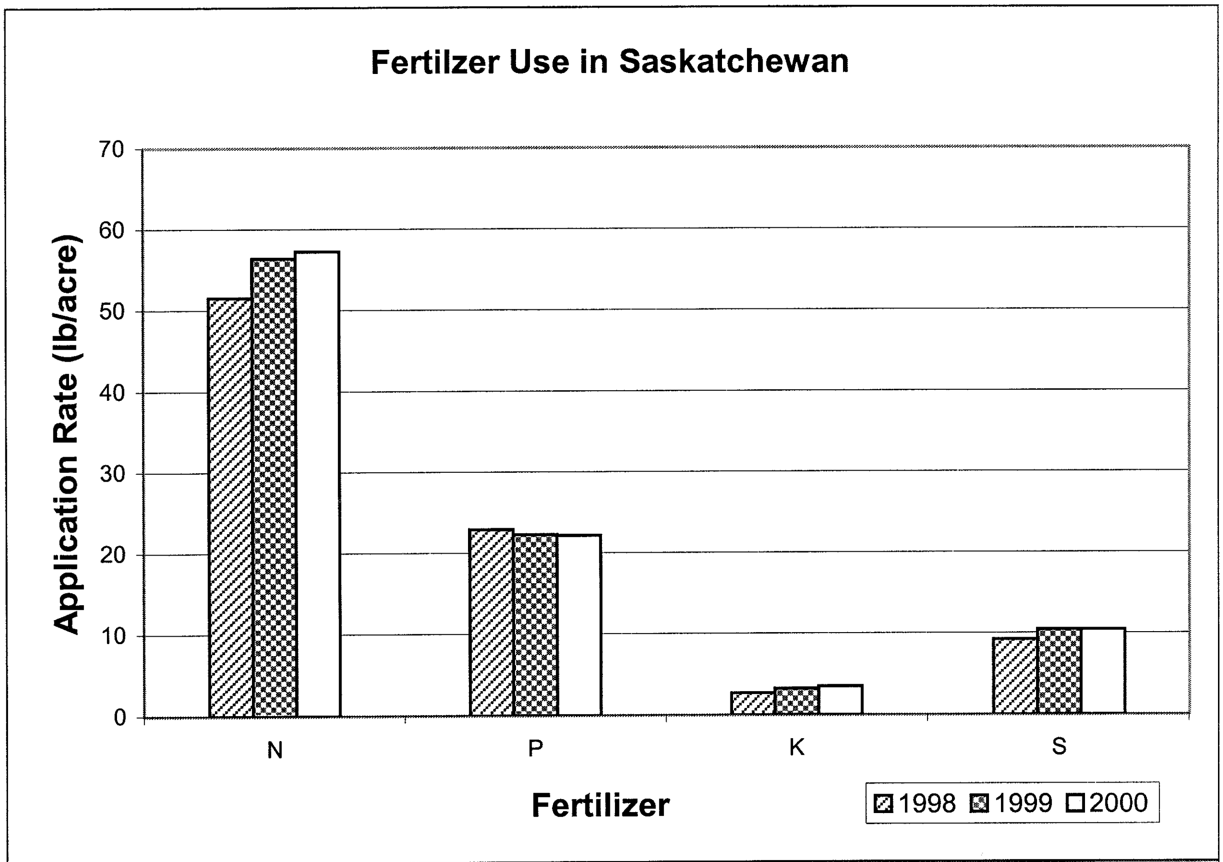

Canola Yields on Stubble vs Fallow
35
30
25
20
15
10
5
0
Yield (bu/ac)
1997
1998
1999
2000
Year
Stubble
Fallow

Figure A7.


Fertilzer Use in Saskatchewan
Application Rate (lb/acre)
70
60
50
40
30
20
10
0
N
P
K
S
Fertilizer
1998
1999
2000

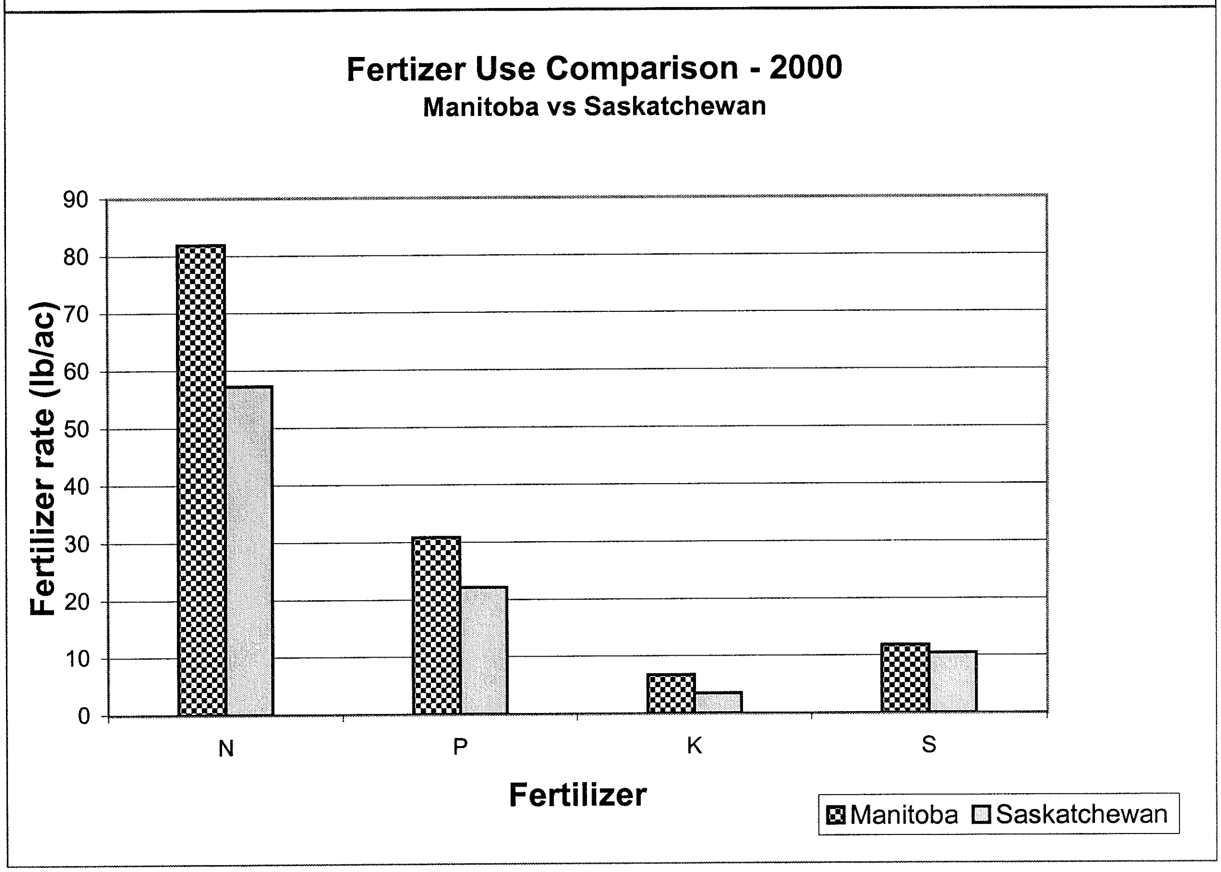
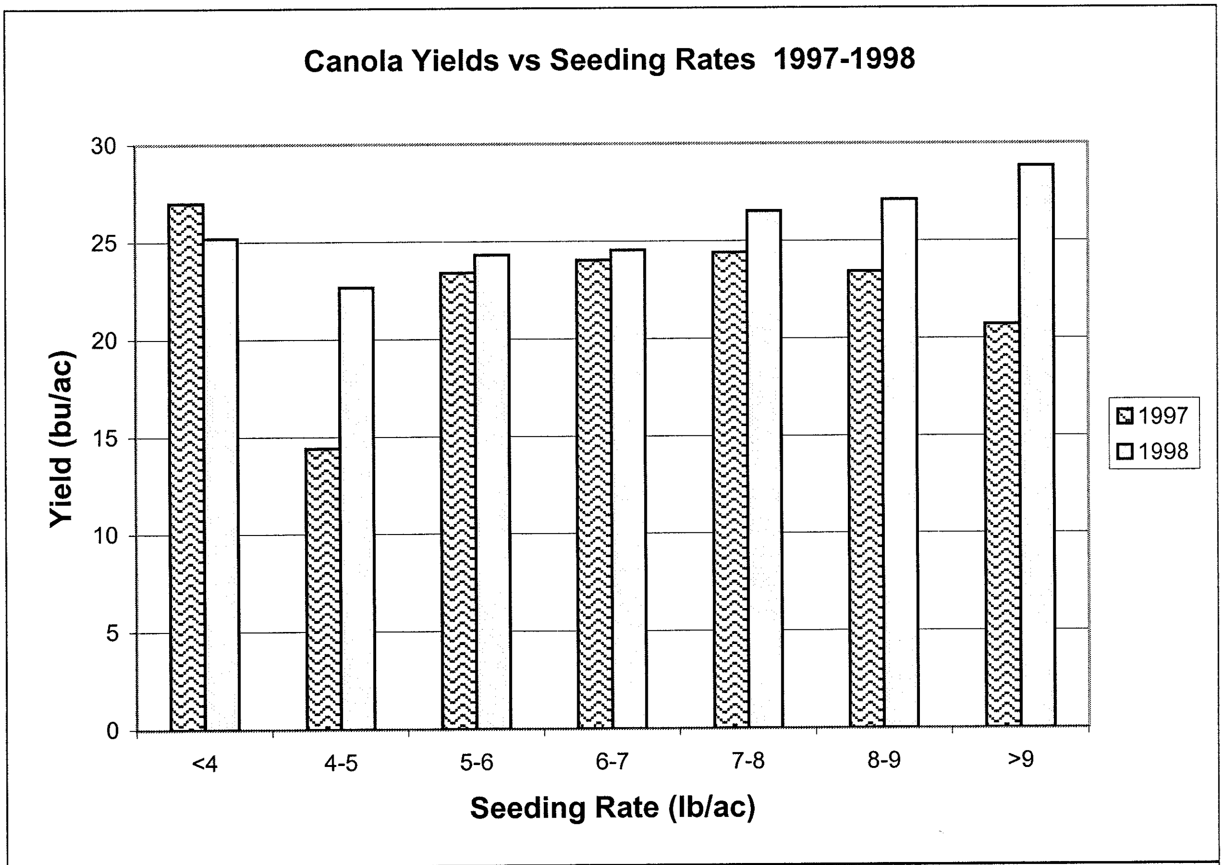
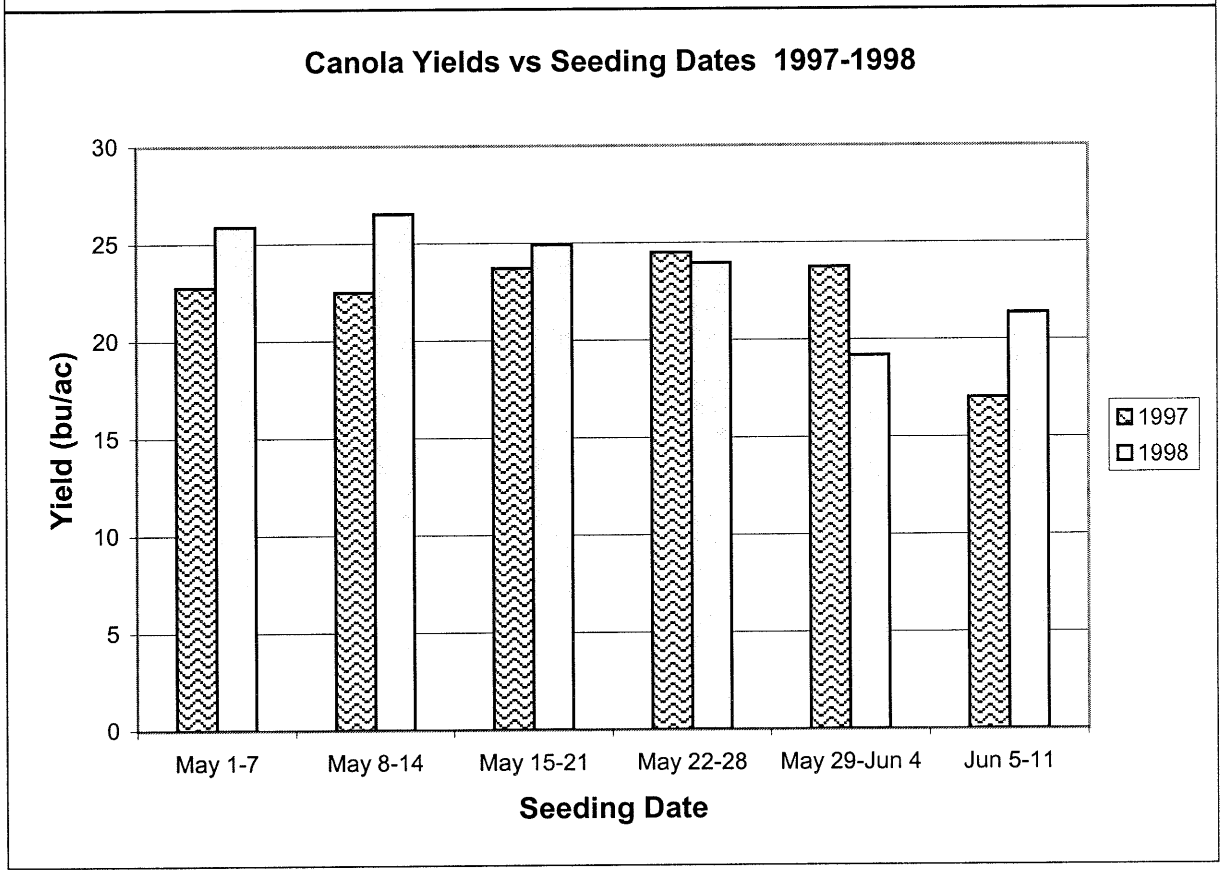

Fertizer Use Comparison - 2000
Manitoba vs Saskatchewan
Fertilizer rate (lb/ac)
90
80
70
60
50
40
30
20
10
0
N
P
K
S
Fertilizer
Manitoba
Saskatchewan

Figure A8.

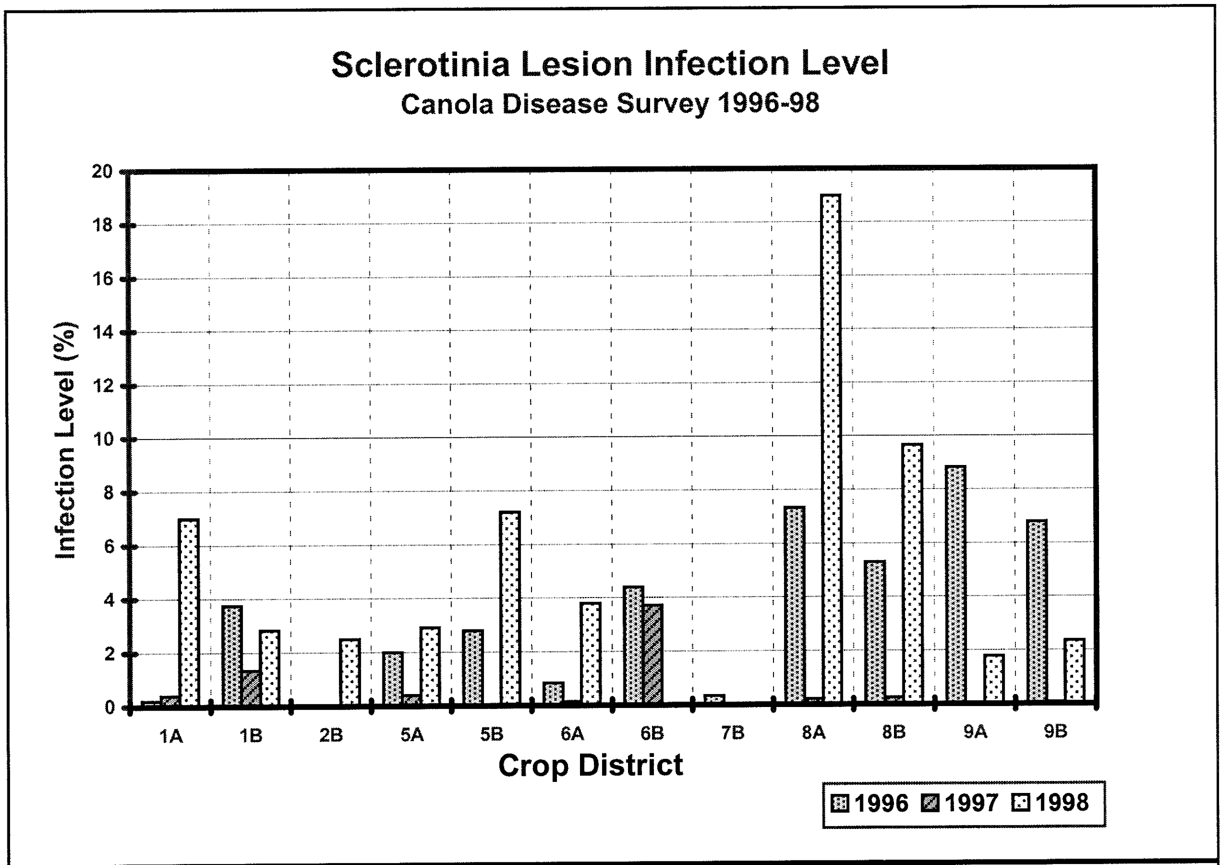


Canola Yields vs Seeding Rates 1997-1998
Yield (bu/ac)
30
25
20
15
10
5
0
<4
4-5
5-6
6-7
7-8
8-9
>9
Seeding Rate (lb/ac)
1997
1998

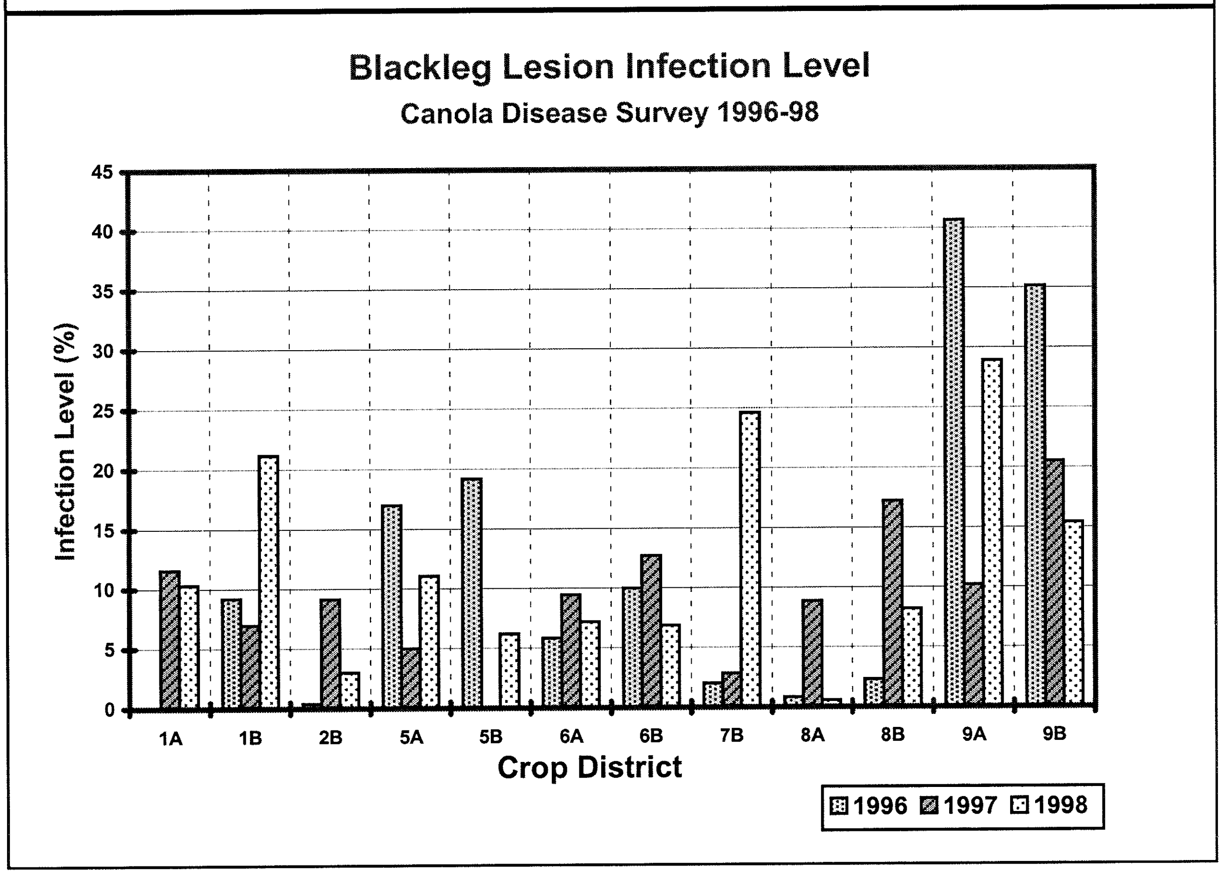


Canola Yields vs Seeding Dates 1997-1998
Yield (bu/ac)
30
25
20
15
10
5
0
May 1-7
May 8-14
May 15-21
May 22-28
May 29-Jun 4
Jun 5-11
Seeding Date
1997
1998

Figure A9.

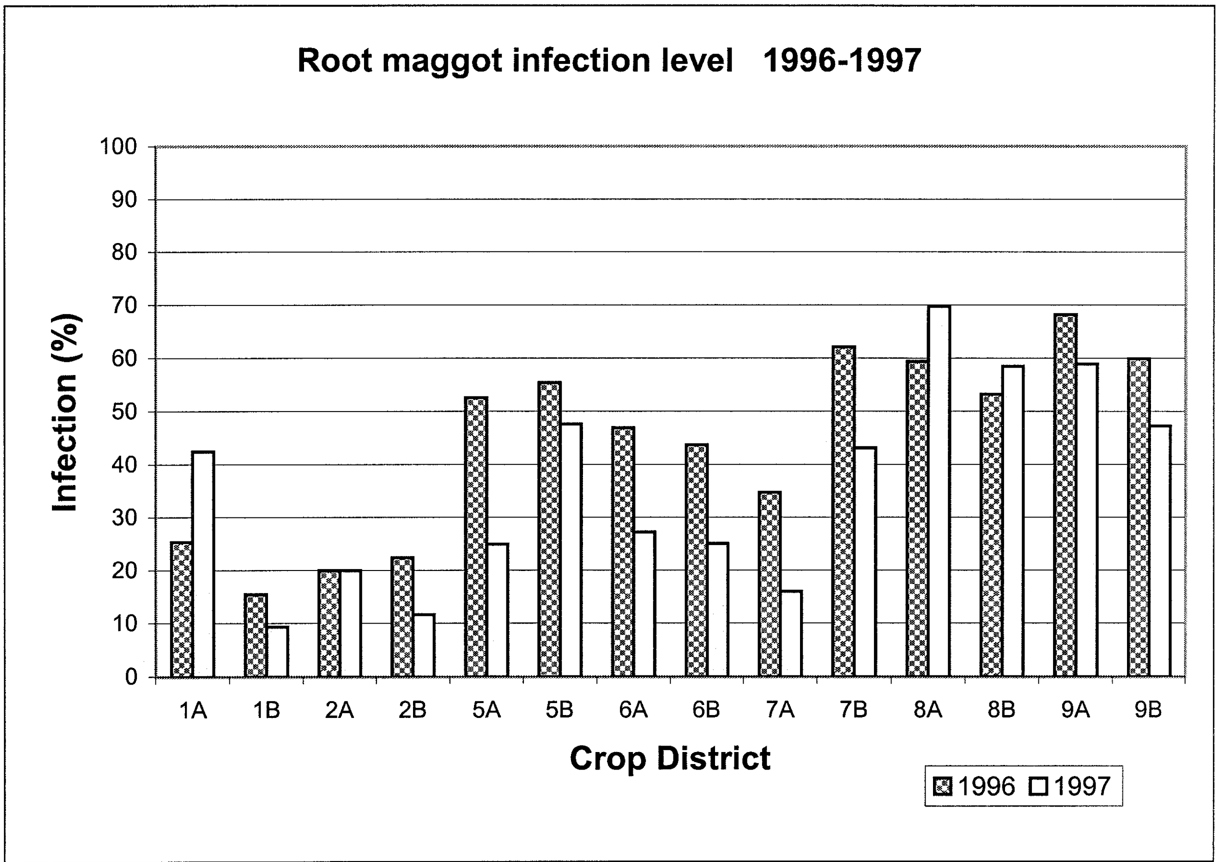


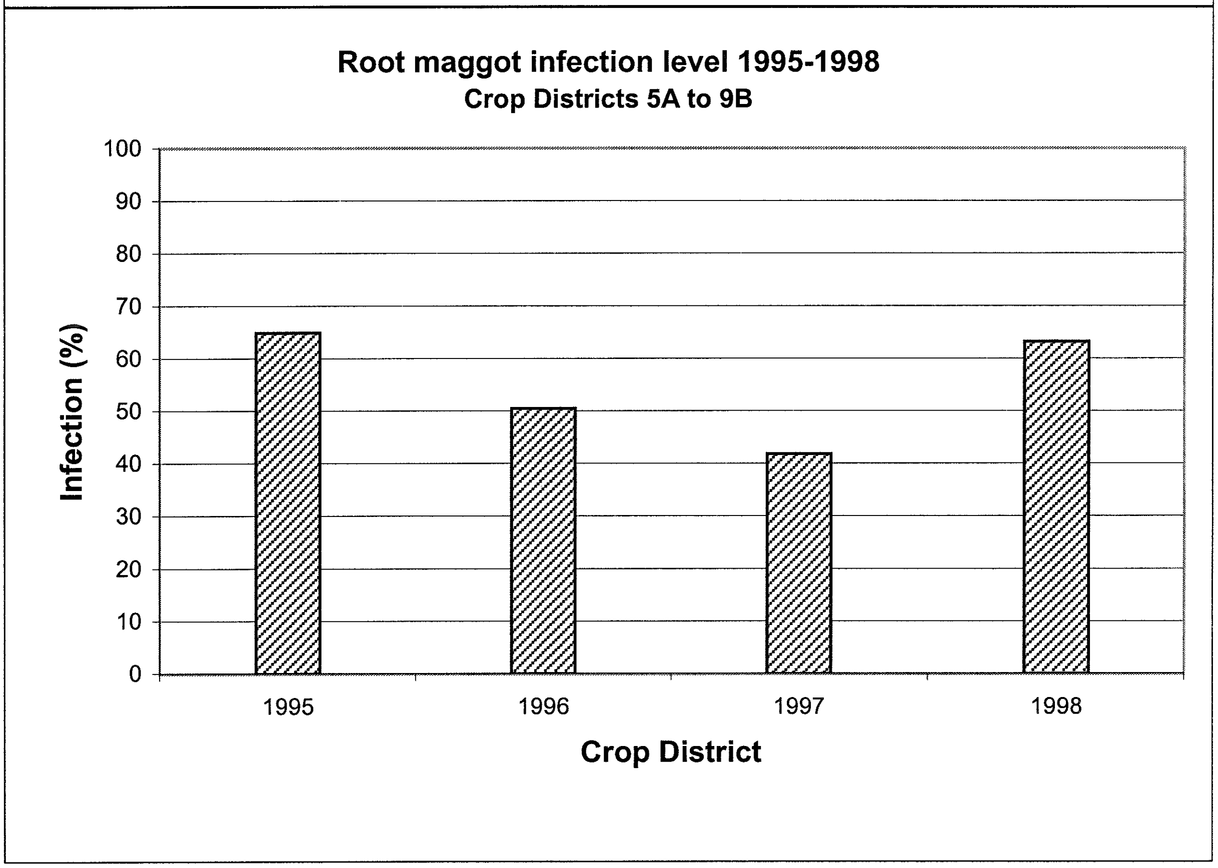
Sclerotinia Lesion Infection Level
Canola Disease Survey 1996-98
Infection Level (%)
20
18
16
14
12
10
8
6
4
2
0
1A
1B
2B
5A
5B
6A
6B
7B
8A
8B
9A
9B
Crop District
1996
1997
1998



Blackleg Lesion Infection Level
Canola Disease Survey 1996-98
Infection Level (%)
45
40
35
30
25
20
15
10
5
0
1A
1B
2B
5A
5B
6A
6B
7B
8A
8B
9A
9B
Crop District
1996
1997
1998

Figure A10.


Root maggot infection level 1996-1997
Infection (%)
100
90
80
70
60
50
40
30
20
10
0
1A
1B
2A
2B
5A
5B
6A
6B
7A
7B
8A
8B
9A
9B
Crop District
1996
1997


Root maggot infection level 1995-1998
Crop Districts 5A to 9B
Infection (%)
100
90
80
70
60
50
40
30
20
10
0
1995
1996
1997
1998
Crop District