DISSERTATION

FIELD BIOLOGY OF RUSSIAN WHEAT APHID, *DIURAPHIS NOXIA* (MORDVILKO) (HOMOPTERA: APHIDIDAE) ON WHEATS DIFFERING IN CATEGORIES OF RESISTANCE.

Submitted by

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In partial fulfillment of requirements

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY HASSAN YAHAYA AL-AYEDH ENTITLED FIELD BIOLOGY OF RUSSIAN WHEAT APHID, *DIURAPHIS NOXIA* (MORDVILKO) (HOMOPTERA: APHIDIDAE) ON WHEATS DIFFERING IN CATEGORIES OF RESISTANCE BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Advisor

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ABSTRACT OF DISSERTATION

FIELD BIOLOGY OF RUSSIAN WHEAT APHID, *DIURAPHIS NOXIA* (MORDVILKO) (HOMOPTERA: APHIDIDAE) ON WHEATS DIFFERING IN CATEGORIES OF RESISTANCE.

The Russian wheat aphid, *Diuraphis noxia* (Mordvilko), is a serious pest of small grains in certain regions of the United States. An economically and environmentally effective option for controlling this pest is the use of resistant cultivars. Two resistant genotypes (CO 940626 that contains resistance gene Dn4 and CO 940252 that contains resistance gene Dn6) were tested for their effects on Russian wheat aphid field biology in 1996, 1998 and 1999. Russian wheat aphid densities were low on resistant wheat genotypes as compared to those of the susceptible wheat cultivar TAM 107. Based on Russian wheat aphid age structure, the two resistant genotypes affected the Russian wheat aphid developmental biology. A higher proportion of first instars was produced, but lower proportions of second-third, fourth instar and adults were observed, indicating an antibiosis resistance category. Both of these resistant genotypes had similar effects on aphid development. The infestation levels were distinct over the study period in all three years. The susceptible cultivar had more parasitization of the Russian wheat aphid than the resistant genotypes. Seed quality was affected by the highest level of infestation.

Biotic and abiotic factors were examined for their effects on Russian wheat aphid on the resistant and susceptible wheat genotypes in 1997-1998 and in 1998-1999. Combined natural enemies did not affect Russian wheat aphid mortality on resistant wheats but did on the susceptible cultivar. Exclusion of natural enemies with insecticide treatments had no effect on activity of natural enemies. Rainfall affected the Russian wheat aphid significantly more on resistant wheats than on the susceptible, because of the flat leaves of resistant wheats. Accumulative degree hours below 0°C reduced aphid population densities during winter. On the other hand, accumulative degree hours above 20°C negatively affected aphid densities later in the season.

A laboratory experiment showed antibiosis as the primary resistance category in the Zadoks 13 growth stage, antixenosis and some indication of tolerance also were observed. However, tolerance was not clearly indicated as one of the category.

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Dedication

This work is dedicated to my precious family, my wife Zahra and my two children. Lama and Yazid.

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Field biology of Russian wheat aphid on wheats differing in category of resistance

Introduction

The Russian wheat aphid. *Diuraphis noxia* (Mordvilko) (Homoptera: Aphididae). is an important pest of wheat. *Triticum aestivum* L., and other small grains in the Great Plains. This insect was first recognized as a cereal pest by Mordvilko in Russia in 1912 (Poprawski et al. 1992). It is indigenous to southern Russia, Iran and Afghanistan. The Russian wheat aphid was introduced into South Africa in 1978 and into Mexico in 1980 (Aalbersberg et al. 1987a). It was first reported from the United States in Texas in 1986 (Stoetzel 1987). Since then it has spread into 16 additional western states. Direct losses to Russian wheat aphid have ranged from $129.3 million in 1988 to $6.4 million in 1991. From 1987 to 1993, estimated direct US losses were $432.5 million (Morrison and Peairs 1998).

Economic. environmental and food safety considerations associated with intensive use of insecticides have stimulated the development of an integrated pest management approach for Russian wheat aphid. employing wise use of insecticides. cultural practices. resistant host plants. and biological control. The following studies focused on resistant wheats and their effects on Russian wheat aphid field biology.

Field biology of Russian wheat aphid.

The Russian wheat aphid can be either holocyclic or anholocyclic. Holocyclic Russian wheat aphids reproduce sexually during the fall and overwinter as eggs. Parthenogenetic (viviparity) reproduction occurs from the spring to the next fall. Anholocyclic aphids undergo parthenogenetic viviparous reproduction throughout the year. In North America Russian wheat aphid is anholocyclic (Kiriac et al. 1990).

Armstrong and Peairs (1996) and Hammon and Peairs (1992) observed only anholocyclic Russian wheat aphids in Colorado.

Russian wheat aphid seasonal density varies in the field. Archer and Bynum (1993) reported that in Texas aphid densities were low in the fall for the years 1987-1989. Greenbug, *Schizaphis graminum* (Rondani), was the most common aphid, comprising 44%-72%, of all aphids in November and December in fall 1987. By January 1988, Russian wheat aphid accounted for >95% of all aphids. A similar trend was observed for Russian wheat aphid from April until harvest when it comprised 90% of all aphids, with the remainder being mostly *S. graminum* and the bird cherry-oat aphid *Rhopalosiphum padi* (L.). Russian wheat aphids disperse among fields and regions throughout the fall. The low number of Russian wheat aphids in the fall suggests that summer survival is poor. Winter cold, even in the relatively mild Texas panhandle favored survival of the Russian wheat aphid over greenbug or bird cherry-oat aphids.

Seasonal activity of aphids is well marked for some species. The green spruce aphid, *Elatobium abietinum* (Walker), has a single seasonal peak in spring, hop aphid, *Phorodon humuli* (Schrank), has two peaks in spring and summer and *R. padi* has three seasonal peaks in spring, summer and between summer and winter (Dixon 1998). Peairs (1990) reported that Russian wheat aphid population densities were low in the fall in Colorado, with further decrease during the winter, followed by rapid spring increases. There was some variation in this pattern between northeastern and southeastern Colorado.

Greenbug had been affected by cereals that were partially resistant, reducing the frequency of outbreaks of this aphid in the early part of this century in North America

(Dixon 1989). The use of plant resistance for reducing the aphid infestation has been known for some time.

Russian wheat aphid has four to six instars from birth to adult (Aalbersberg et al. 1987b). According to Hughes (1972), aphid instar knowledge is very important for construction of time-specific life-tables, which in turn allows evaluation of the impact of mortality factors under field conditions. Olsen et al. (1993) used antenna segment morphology to distinguish among Russian wheat aphid instars (first instar, second instar, third instar, fourth instar) and adults in measuring development. The first instar nymphs have 4 antennal segments. Second and third instar nymphs both have 5 antennal segments, but with distinct segment ratios. Fourth instar nymphs and adults both have six segments, again with different length ratios. It is most challenging to differentiate between second and third instars.

Plant resistant can affect insect development. Antibiosis can reduce the rate of population increase by reducing the reproduction rate and survival of insects (Panda and Khush 1995). Russian wheat aphid developmental rate had been affected by wheat resistance (Formusoh et al. 1992; Webster et al. 1991; Webster et al. 1993).

Aphid development can be affected by many factors such as temperature, overcrowding and host quality. Russian wheat aphids are typical r-strategists (Hewitt 1988). Population densities increase with increasing temperature, with greatest abundance occurring in later crop growth stages.

Biological control of Russian wheat aphid:

Biological control is the action of parasites, predators, and pathogens in maintaining undesirable insects below certain level. Over 100 species of natural enemies have been associated with Russian wheat aphid worldwide (Mohamed 1995). Many of these, mostly coccinellids and braconids, have been introduced to over 20 countries in Asia, Europe, Africa and South America. Coccinellids are often abundant in Russian wheat aphid infested wheat, but may not be effective predators due to limited ability to search within rolled leaves (Kauffman and La Roche 1994). In Colorado, Mohamed (1995) listed potential Russian wheat aphid natural enemies (Tables 1.1, 1.2). The predators included spiders (5 species), carabids (15 species), coccinellids (12 species), syrphids (5 species), nabids (2 species) and chrysopids (2 species) (Table 1.1).

Table 1.1. Potential predators of Russian wheat aphid collected from the host plants. Piedmont Farm (Larimer, Co., Colorado), 1991 - 1994 (Mohamed 1995).

Order	Family	Species
Araneae	Lycosidae	*Pardosa sternalis* (Thorell)
		Pardosa spp.
		Schizocosa avida (Walckenaer)
	Tetragnathidae	*Tetragnatha labariosa* (Hentz)
	Thomisidae	*Misumenaops* asperatus (Hentz)
		Thomisidae spp.
Coleoptera	Carabidae	*Agonum placidum* (Say)
		Agonum subsericum(LeConte)
		Amara carinata (LeConte)
		Amara coelebs (Hayward)
		Amara fracta (LeConte)
		Amara littoralis (Mannerheim)
		Amara quenseli (Schoenherr)
		Anisodactylus harrisii(LeConte)
		Bembidion nitidum (Kirby)
		Harpalus amputatus (Say)
		Harpalus pensylvanicus (DeGeer)
		*Loriecera pilicornis(*Fabricius)
		Poecilus lucublandus (Say)
		Poecilus scitulus (LeConte)
		Selenophorus planipennis(LeConte)
	Coccinellidae	*Brachyacantha* spp.
		Coccinella septempunctata (L.)
		Coccinella transversoguttata - Richardsoni Brown
		Coleomegilla maculata (DeGeer)
		Exochomus aethiops (Bland)
		Hippodamia convergens Guerin
		Hippodamia parenthesis (Say)
		Hippodamia sinuata crotchi Casey
		Hyperaspis quadrivittata LeConte
		Paranaemia vittigera Mannerheim

Table 1.1. (cont) Potential predators of Russian wheat aphid collected from the aphid host plants. Piedmont Farm 8 (Larimer, Co., Colorado). 1991 - 1994 (Mohamed 1995).

Order	Family	Species
	Coccinellidae	*Scymnus brullei* Mulstan *Scymnus postpictus* Casey
Diptera	Syrphidae	*Allograpta oblique* Say *Eupeodes volucris* Osten Sacken *Helophilus latifrons* Loew *Mesogramma marginata* Say *Syrphus opinator* Osten Sacken
Hemiptera	Nabidae	*Nabis alternatus* Parsh *Nabis americoferus* Carayon
Neuroptera	Chrysopidae	*Chrysoperla plorabunda* (Fitch) *Eremochrysa Sabulosa* Bank

The parasitoids included braconids (1 species), pteromalids (2 species), chairpids (1 species) and megaspilids (1 speci :s) (Table 1.2).

Table 1.2. Parasitoids of Russian wheat aphid collected from the aphid host plants. Piedmont Farm (Larimer, Co., Colorado), 1991 - 1994 (Mohamed 1995).

Order	Family	Species
Hymenoptera	Braconidae	*Diaeretiella rapae* (M'Intoch)
	Pteromalidae	*Asaphes suspensus* (*Nees*) *Asaphes californicus* (Girault)
	Chairpidae	*Aloxysta megourae* (Ashmead)
	Megaspilidae	*Dendrocerus* sp

Host plant resistance and biological control.

The use of plant resistance and biological control strategies are important components of integrated pest management programs. Some studies have focused on plant secondary compounds or certain morphological characteristics such as trichomes or waxy layers which interfere with the natural enemies. In susceptible wheats, Russian wheat aphids prevent leaf unrolling. However, some resistant wheats are able to unroll leaves in the presence of Russian wheat aphid. This exposes the aphid to its natural enemies (Formusoh and Wilde 1993; Reed et al. 1991). Reed et al. (1991) showed higher parasitism rate of *Diaeretiella rapae* on plant species resistant to leaf rolling. In a similar study, Messina et al. (1997) concluded that tested predators had a better chance in capturing the aphids on unrolled grass leaves than rolled grass leaves. However, Reed et al. (1991) stated that the high level of antibiosis in wheat resulted in smaller *D. rapae* parasitoids and antibiotic plants thus were not preferable. On the other hand, Farid et al. (1998) found that two resistant wheat lines, PI 137739 and PI 262660, increased the percent of *D. rapae* emerging from aphids and that antibiosis resistance was compatible with *D. rapae* for integrated management of Russian wheat aphid. According to Brewer et al. (1998), parasitism rates were approximately equal on uncurled leaves of resistant and curled leaves of susceptible barley. They concluded that plant resistance and biocontrol were compatible management strategies.

Russian wheat aphid density can affect wheat quality and quantity. Girma et al. (1993) reported that 7 % stem infestation during early fall caused up to 6 % yield loss. Also, a similar infestation level, allowed to continue throughout spring, caused a 45 %

yield loss. Grain quality in terms of 100-kernel weight and protein content also was reduced by spring infestations (Girma et al. 1993).

I hypothesize that different categories of aphid resistant in wheat will have different effects on Russian wheat aphid field biology in Colorado. My objectives were to: (1) examine the population dynamics of Russian wheat aphid on three wheats differing in category of resistance; and (2) determine the effect of *D. noxia* infestation on grain yield and quality of each wheat.

Materials and Methods

Plant materials.

Three wheat lines were used: (1) CO940626 containing the Dn4 resistant gene with pedigree CO850034/T-57//5* TAM 107; (2) CO940252 containing the Dn6 resistant gene with pedigree TAM 107//PI243781/CO850260, and (3) the susceptible wheat 'TAM 107' (J. S. Quick, Department of Soil and Crop Sciences, Colorado State University, personal communication).

Aphid colony.

The *D. noxia* colony was established from aphids collected from volunteer wheat in August of each year. The colony was maintained in a growth chamber and a greenhouse on a mixture of susceptible wheat and barley seedlings (J. Rudolph, Department of Bioagricultural Sciences and Pest Management, Colorado State University, personal communication).

Field treatments and infestation methods.

Aphid numbers were manipulated to produce three levels of Russian wheat aphid infestation: low, medium and high. The low level was not infested and was treated with disulfoton (Di-Syston 15G) (Miles Inc. Agriculture Division, Kansas City, MO) applied at the rate of 0.49 kg (AI)/ ha to control natural infestation from migrants (Armstrong et al. 1990) (Table 1.3). The insecticide was lightly incorporated into the soil surface by raking after application. The first application was made at spring regrowth (Table 1.3). The medium level was infested with approximately 25 aphids per plant at spring regrowth (growth stage 30-31 (Zadoks et al. 1974)). Russian wheat aphids were mixed with dry

Cream of Wheat(R) cereal (Nabisco. Inc. east Hanover. N.J.). and applied to the plant with a Davis insect inoculator in a manner similar to that described by Calhoun et al. (1990). The highest level of infestation was approximately 50 aphids per plant, applied in similar manner. According to Rafi et al. (1996) 0, 20, 40 and 80 aphids per plants resulted in significant variation in population density increases. These infestation levels were intended to achieve similar variation within limits of aphid production capacity.

Field layout and crop management.

Field operations are summarized in Table 1.3. Border rows and buffers were planted to TAM 107 with a tractor-mounted plot planter. However, each 0.76m x 2.25m plot was hand-planted with a wheel planter, except the 1999 season, when a tractor-mounted precision plot planter was used.

Table 1.3. Summary of field activities during the study periods. Agricultural Research. Development and Education Center. Fort Collins. CO.

Activities / Years	1996-1997	1997-1998	1998-1999
Pre irrigation	August 13, 1995	August 18. 1997	[2]September 24. 1998
Planting	September 20. 1995	September 11, 1997	September 10. 1998
Insecticide	November 13, 1995	February 2, 1998	March 3, 1999
Infestations	[1]November 8, 1995 [1]April 13, 1996 [1]April 27, 1996	February 27, 1998	March 15, 1999
Sampling started	April 22, 1996	May 4, 1998	April 6. 1999
Harvest	July 28, 1996	July 23, 1998	July 22, 1999

[1]Infestations were repeated three times because of the low survival due to poor colony condition.
[2] Irrigation were made only 1998-1999 season wks after planting.

Experimental design.

A factorial design was used with six replicates and nine treatments (Steel and Torrie 1980). The analysis of variance model used is shown in Table 1.4.

Table 1.4. Analysis of variance for a two - factor treatment design in randomized complete block experiment design.

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	F
Total	53	SS Total		
Block	5	SS Block	MSR	F_{Reps}
Aphid level	2	SSAphids	MSAphids	$F_{aphid\ level}$
Wheat line	2	SSWheat	MSWheat	$F_{wheat\ line}$
Aphid level x wheat line	4	SS(Aphids* Wheat)	MS(Aphids* Wheat)	$F_{aphidsxwheat}$
Error	40	SSE	MSE	

The following model was applied :

$$Y_{ijk} = M + \rho P_k + A_i + \beta B_j + (AB\beta)_{ij} + \Sigma E_{ijk} \text{ (Steel and Torrie 1980).}$$

i = Wheat variety. , j = Russian wheat aphids level of infestations (0, 20 and 54).. k = block effect 1.......6.

Sampling and data collection.

The first sample was taken as symptoms first appeared in the spring (Table 1.3). Six tillers per plot were removed twice per wk late in spring until crop maturity. Samples were placed in Ziploc[R] bags (S. C. Johnson & Son, Inc., Racine, WI) labeled with the date and plot number. The bags were put in a cooler for transport to the laboratory. Samples were examined for parasitoid mummies and then placed individually in Berlese funnels for 24 hours (Armstrong et al. 1991). Russian wheat aphids were extracted into jars containing 80% ethanol, and labeled with the corresponding plot number, for subsequent sorting and counting by life stage. Life stages were separated according to Olsen et al. (1993).

Biological control agents were determined by two methods. First, parasitoid mummies were counted before placing samples in Berlese funnels. Predators collected at each tiller sample from 50 sweeps with a standard sweep net (37.5cm diameter) were also counted. Identification and counting were done on the preserved mature and immature stages of aphid predators. These were then it was compared with determined materials in the C. P. Gillette arthropod museum at Colorado State University. Russian wheat aphid samples, predators and parasitoids specimens were deposited as vouchers in the same museum.

The effect of *D. noxia* infestation on grain yield and quality was determined by harvesting one m of unsampled row from each plot. The number of spikes, total seed weight and thousand kernel weight were determined. Approximately 5 mg of the harvested seeds were ground to determine the percent protein with a Dickey John GAC III near infrared grain analysis computer (B. Clifford, Department of Soil and Crop Science, Colorado State University, personal communication).

Data management and statistical analysis.

Data were arranged in columns and rows using the spreadsheet program Corel (R) Quattro Pro (R) Suite 8. Then data were analyzed using SAS (SAS 1996). Data were tested for normality and an appropriate transformation was applied as if needed, based on the residual plot shape (SAS 1996). Means were compared by Fisher's LSD method if P > F was < 0.05 and by Bonferroni's method if it was > 0.05 (Milliken and Johnson

1984). All analyses of results, including LSD value and Bonferroni's value (reported as Dunn procedure), are reported in tables. In addition, a single-degree contrast was used to compare both resistant wheats to TAM 107.

The proportions of each developmental stage comprising a sample also were analyzed using SAS. Proportions were transformed by the arcsine method (Little and Hills 1987) and analyzed as described above.

Yield and quality parameters were analyzed using the same procedures as described above. However, transformation was not necessary.

Results and Discussion

Population density.

Russian wheat aphid population density was three times to five times greater on susceptible wheat than resistant wheats in 1996, 1998 and 1999, respectively (Figs 1.1, 1.2 and 1.3). Wheat genotype affected aphid population density in 1996 (F=80.01, df=2, P <0.0001), 1998 (F= 30.35, df=2, P <0.0001) and 1999 (F= 25.10, df=2, P <0.0001). Fewer Russian wheat aphids collected from CO 940626 or CO 940252 than from TAM 107 in 1996 (F= 159.15; df=1; P < 0.0001), 1998 (F= 60.63; df=1; P < 0.0001) and 1999 (F= 44.05; df=1; P < 0.0001). This significant effect on Russian wheat aphid density is a response of the effect of different wheat genotypes on aphid biology. Such effects would be expected from antibiotic wheat genotypes. The low Russian wheat aphid density observed in 1999 might be explain in part by competition due to the high density of greenbug, (F= 7.20, df=73, P < 0.0001).

The initial infestation levels resulted in distinct Russian wheat aphid densities (Table 1.5). Infestation level significantly affected aphid population densities in all three years, 1996 (F= 58.94; df=2; P <0.0001), 1998 (F=34.13; df=2; P < 0.0001) and 1999 (F=45.48; df=2; P < 0.0001).

A significant interaction for aphid population density between genotypes and initial aphid density was observed during 1996 (F= 17.65; df=4; P <0.0001), 1998 (F= 12.42; df=4; P <0.0001) and 1999 (F=7.38; df=4; P < 0.0001). Both infestation level and wheat genotypes affected Russian wheat aphid density (Tables 1.6 ,1.7 and 1.8). However, that was not the case in the low infestation level 0 aphids/plants in 1999, which might be due to the low aphid density (Table 1.8).

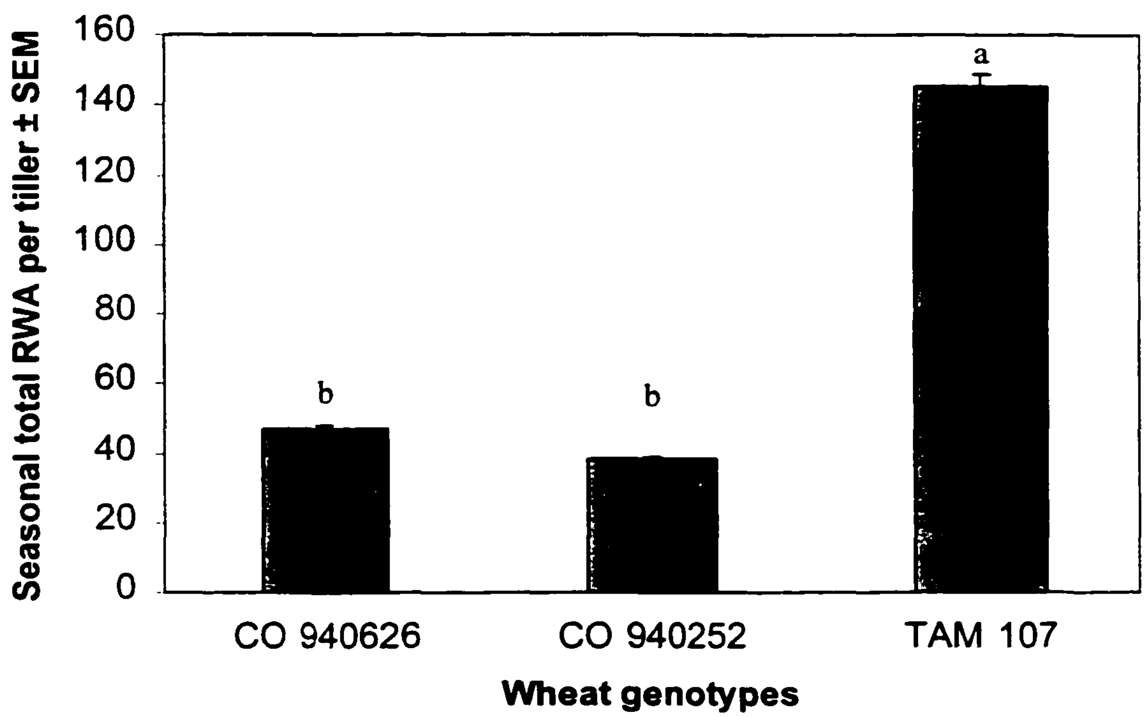

Fig 1.1. Mean (±SEM) Russian wheat aphids (RWA) collected from resistant and susceptible wheats, averaged over 3 initial infestation levels, April-July 1996, Agricultural Research, Development and Education Center, Fort Collins, CO. Bars marked with different letters are significantly different, Fisher protected LSD (α=0.05).

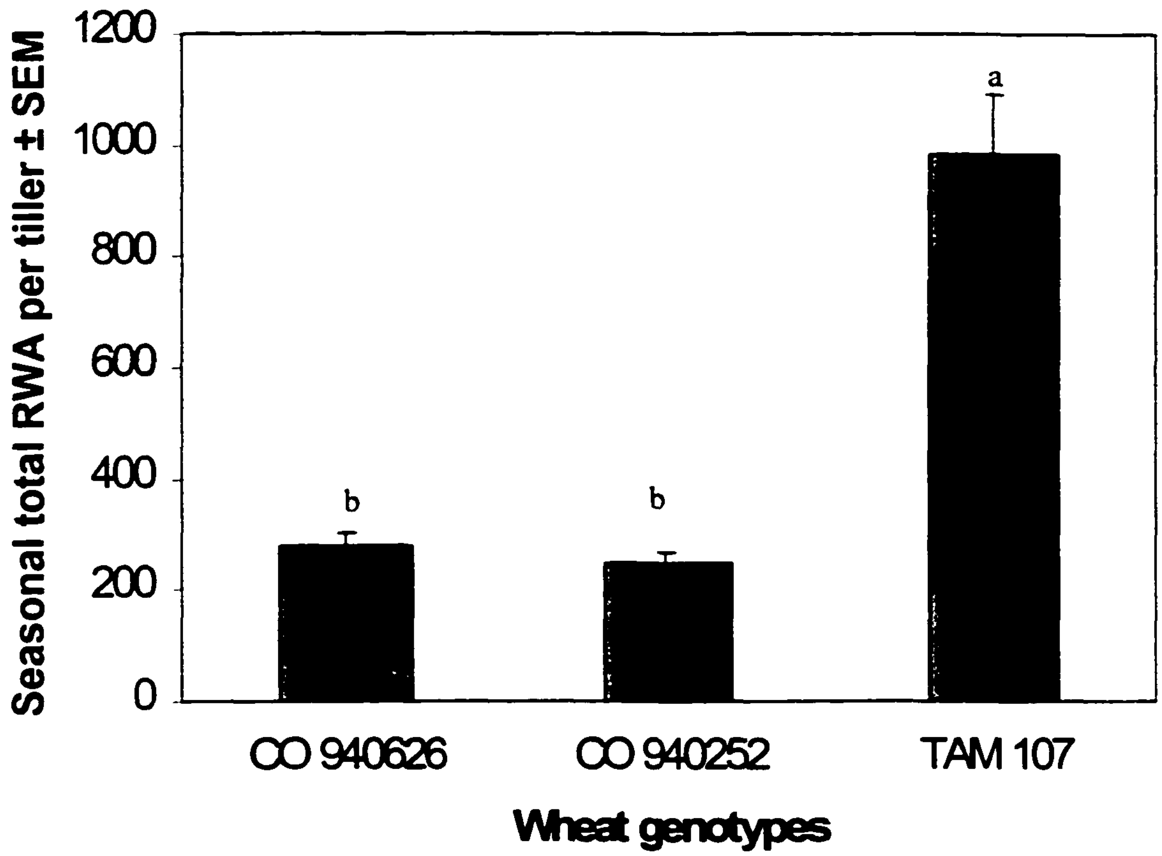

Fig 1.2. Mean (± SEM) Russian wheat aphids (RWA) collected from resistant and susceptible wheats, averaged over 3 initial infestation levels, April-July 1998, Agricultural Research, Development and Education Center, Fort Collins, CO. Bars marked with different letters are significantly different, Fisher protected LSD (α=0.05).

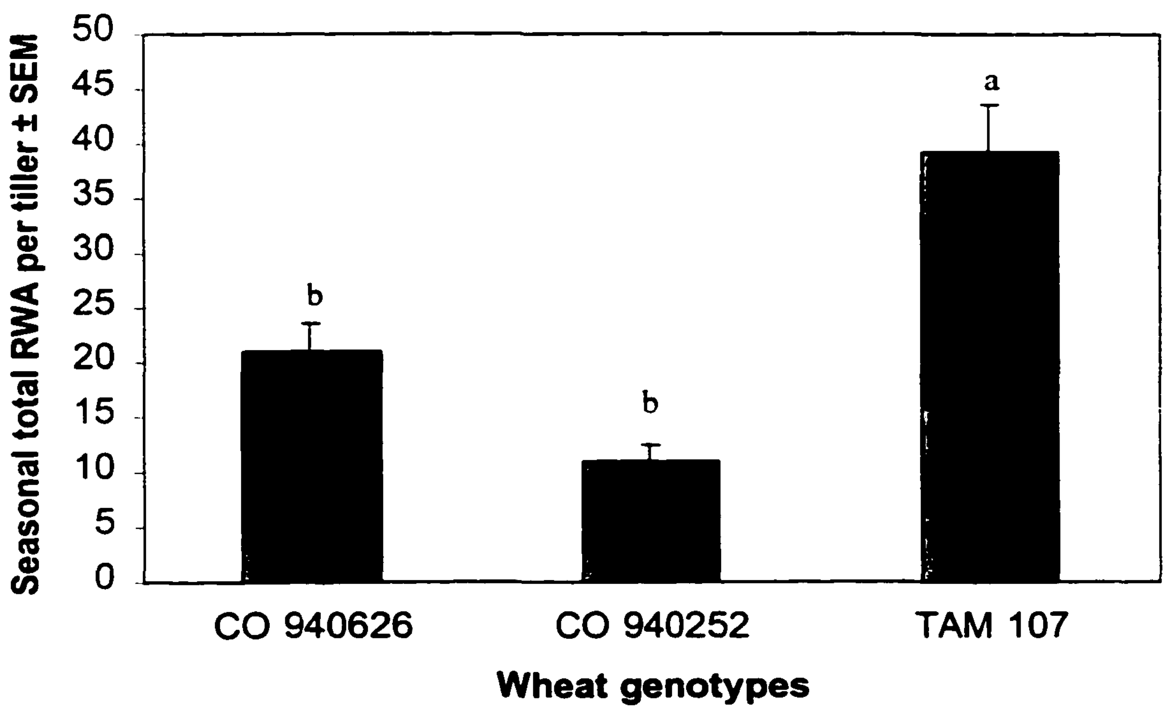

Fig 1.3. Mean (±SEM) Russian wheat aphids (RWA) collected from resistant and susceptible wheats, averaged over 3 initial infestation levels, April-June 1999, Agricultural Research, Development and Education Center, Fort Collins, CO. Bars marked with different letters are significantly different, Fisher protected LSD (α=0.05).

Table 1.5 . Seasonal total number of Russian wheat aphid per tiller collected. 1996. 1998. 1999. Agricultural Research, Developmental and Education Center. Ft. Collins, Colorado.

Infestation levels [1]	Seasonal total Russian wheat aphid per tiller		
	1996	1998	1999
0 aphids/plant	129	441	15
25 aphids/plant	517	2902	173
50 aphids/plant	734	5777	239

[1]Number of Russian wheat aphid originally infested /plant.

Table 1.6. Mean (± SEM) Russian wheat aphids per tiller sampled April-July 1996 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation Levels[1]		
	0 aphids/plant	25 aphids/plant	50 aphids/plant
CO 940626	0.2 ± 0.0b	0.9 ± 0.1b	1.0 ± 0.1b
CO 940252	0.2 ± 0.0b	0.7 ± 0.1b	0.8 ± 0.0b
TAM 107	0.5 ± 0.1a	2.4 ± 0.2a	3.9 ± 0.3a
$LSD_{0.05}$	0.1755	0.4124	0.5687
F- value	7.21	41.99	69.64
$P > F$	0.0009	0.0001	0.0001

Means within a column followed by the same letter (s) are statistically similar according to the mean separation test indicated in first column.

[1]Number of Russian wheat aphid originally infested /plant-tiller on November 8, 1995.

Table 1.7. Mean (± SEM) Russian wheat aphids per tiller sampled April-July 1998 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation Levels [1]		
	0 aphids/plant	25 aphids/plant	50 aphids/plant
CO 940626	1.0 ± 0.2b	7.1 ± 1.1b	10.3 ± 1.4b
CO 940252	1.4 ± 0.2b	6.7 ± 1.0b	8.4 ± 1.0b
TAM 107	2.4 ± 0.4a	18.2 ± 4.3a	45.3 ± 7.2a
$LSD_{0.05}$	0.6819	6.3709	9.634
F- value	8.58	8.14	36.07
P > *F*	0.0002	0.0004	0.0001

Means within a column followed by the same letter (s) are statistically similar according to the mean separation test indicated in first column.
[1]Number of Russian wheat aphid originally infested/plants on February 27, 1998.

Table 1.8. Mean (± SEM)Russian wheat aphids per tiller (± SEM) sampled April-June 1999 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation Levels [1]		
	0 aphids/plant	25 aphids/plant	50 aphids/plant
CO 940626	0.1 ± 0.0a	0.6 ± 0.1b	0.9 ± 0.1b
CO 940252	0.0 ± 0.0a	0.4 ± 0.0b	0.5 ± 0.0c
TAM 107	0.0 ± 0.0a	1.3 ± 0.1a	1.9 ± 0.2a
$Dunn_{0.05}$/ $LSD_{0.05}$	0.0914	0.3265	0.4387
F- value	0.40	14.73	8.01
P > *F*	0.6688	0.0001	0.0004

Means within a column followed by the same letter (s) are statistically similar according to the mean separation test indicated in first column.
[1]Number of Russian wheat aphid originally infested/plant on March 15, 1999.

Seasonal trends for Russian wheat aphid.

The seasonal trends of Russian wheat aphid were similar, although differences in aphid abundance were observed among genotypes and years (Figs 1.4, 1.5,1.6). However, among different wheat genotypes aphid population densities were very low at beginning of sampling periods in all three years, expressing no differences between wheats genotypes. This can be related to the colonization phase of aphids at the beginning of sampling period, which is common to all cereal aphids (Dixon 1998). The number of colonizing aphids depends on the initial infestation level and resistance of the plants. The rate of population increase also depends on weather, plant quality, plant resistance and activity of natural enemies. The decline in density noted on 9-11 June 1996 may have been due to an intense rain fall event (Fig 1.4). Agricultural Research, Development and Education Center received 1.49 cm of rain on 9-10 June 1996. Greater rainfall effects were observed on the two resistant wheats because of the flat leaves in contrast to the curled leaves on the susceptible TAM 107. Messina et al. (1993) observed that Russian wheat aphid alternative hosts with small flat leaves did not protect Russian wheat aphid against rainfall.

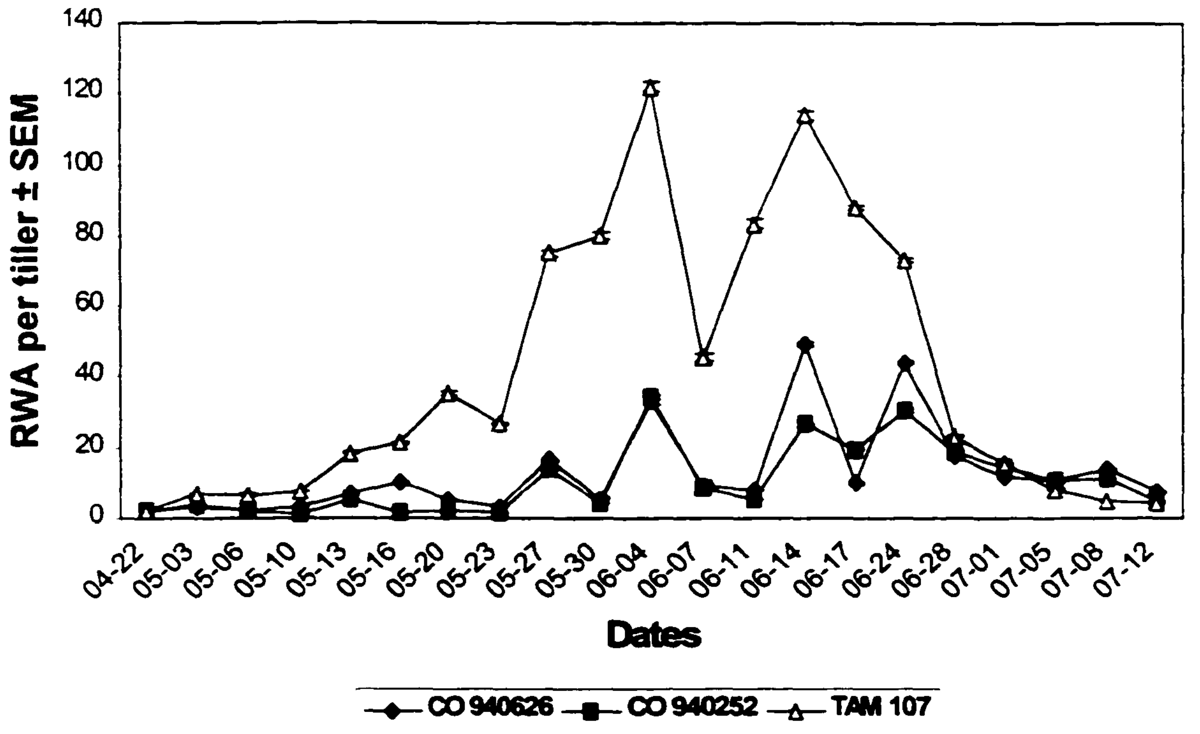

Fig 1.4. Mean (±SEM) Russian wheat aphids (RWA) per tiller collected in 1996 from resistant and susceptible wheats, averaged over 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

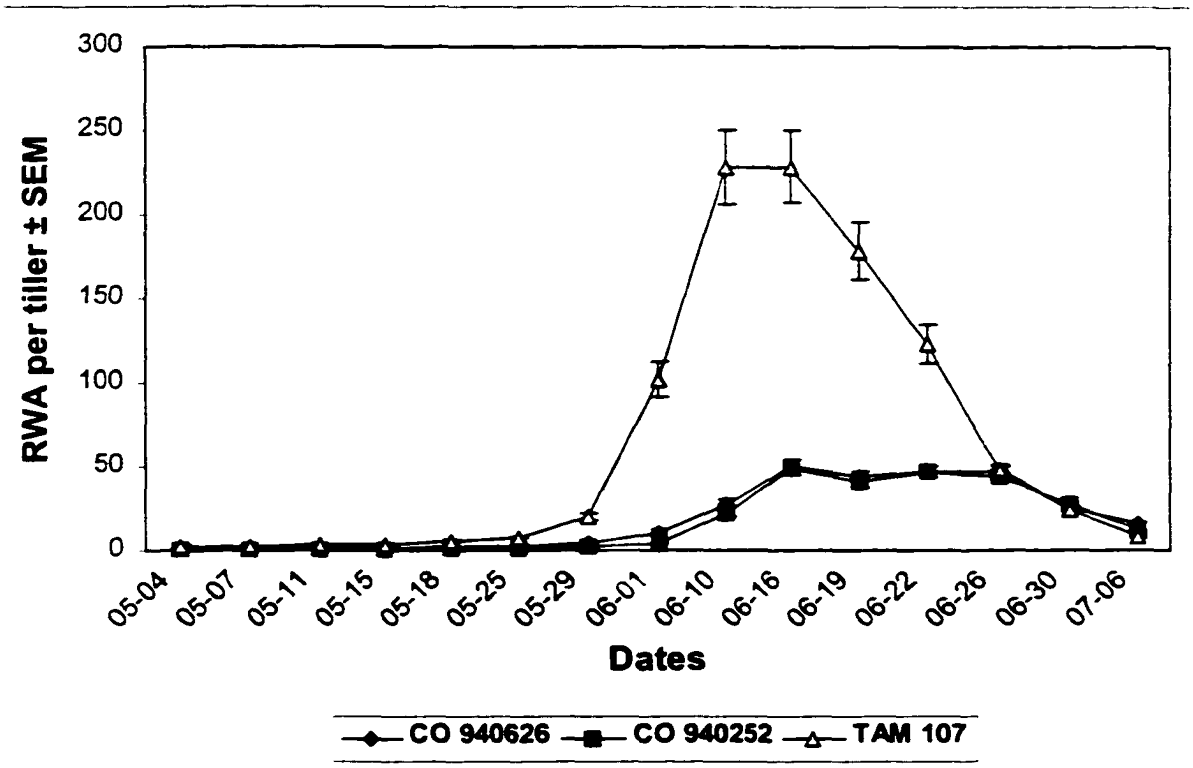

Fig 1.5. Mean (±SEM) Russian wheat aphids (RWA) per tiller collected in 1998 from resistant and susceptible wheats, averaged over 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

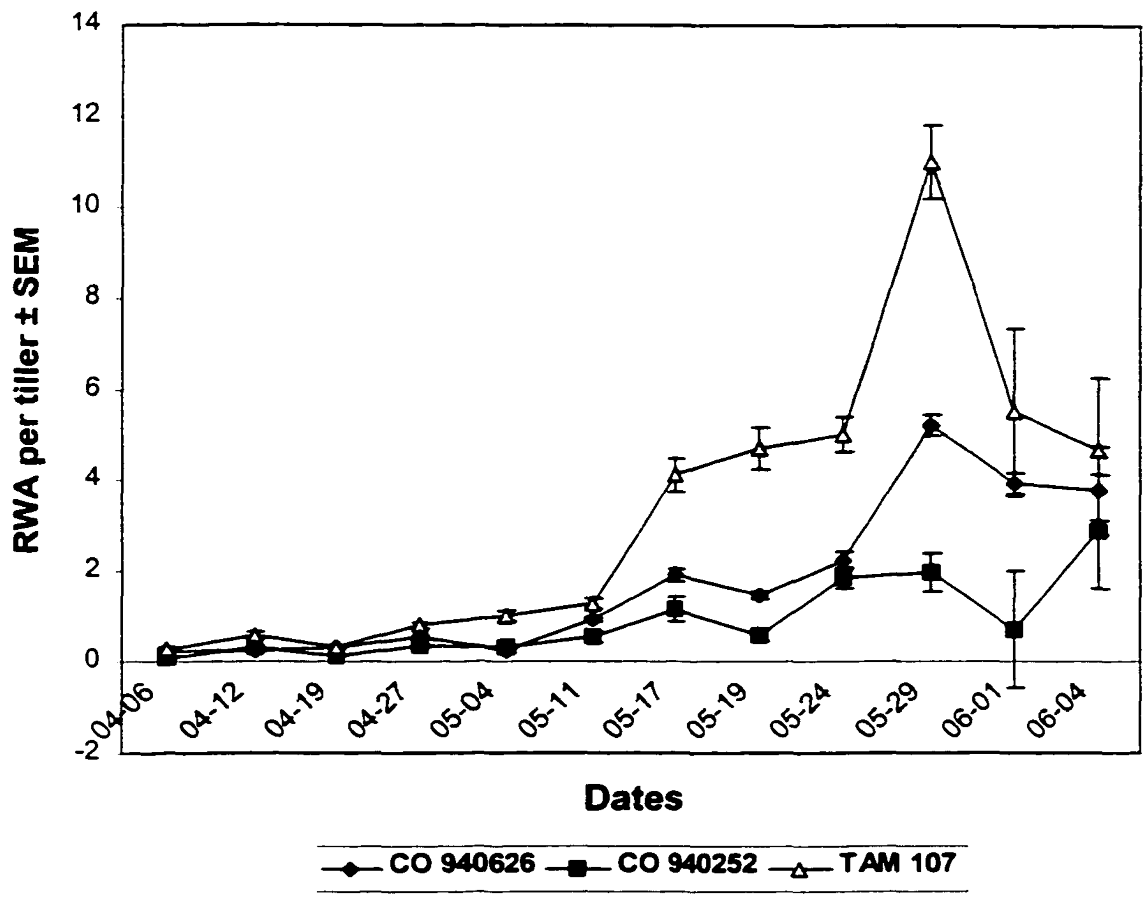

Fig 1.6. Mean (±SEM) Russian wheat aphids (RWA) per tiller collected in 1999 from resistant and susceptible wheats, averaged over 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Effects of wheat genotype on aphid life stages over sampling period.

The seasonal trend of aphid life stage composition also varied among host genotypes due to differences in rates of population growth. Differences were observed among sampling dates in all three years, 1996 ($F = 20.40$, df = 20, $P<0.0001$), 1998 ($F = 19.11$, df = 14, $P<0.0001$) and 1999 ($F = 30.84$, df = 11, $P<0.0001$). In all years the first instars were scarce at the beginning of sampling period (Figs 1.7, 1.8 and 1.9). After 7 sampling dates, genotypic effects on the Russian wheat aphid first instar population were observed. This delay in expression of genotypic differences may have been due to colonization phase mentioned above or maternal effects (Quisenberry and Schotzko 1994). Aphids used for infestation were reared on susceptible genotypes, so several generations would be necessary before the effect of resistant wheat genotypes on aphid development would be expressed.

On the other hand the delays in expressing the effects of different wheat genotype were observed in the second-third instar, fourth instar and adult proportions (Figs 1.10-1.15). These are all indication of an effects of antibiosis on the aphids due to different wheat genotypes. Crop maturity affected seasonal trends since TAM 107 matured more quickly than resistant wheats, reducing differences in aphid abundance at the end of the season.

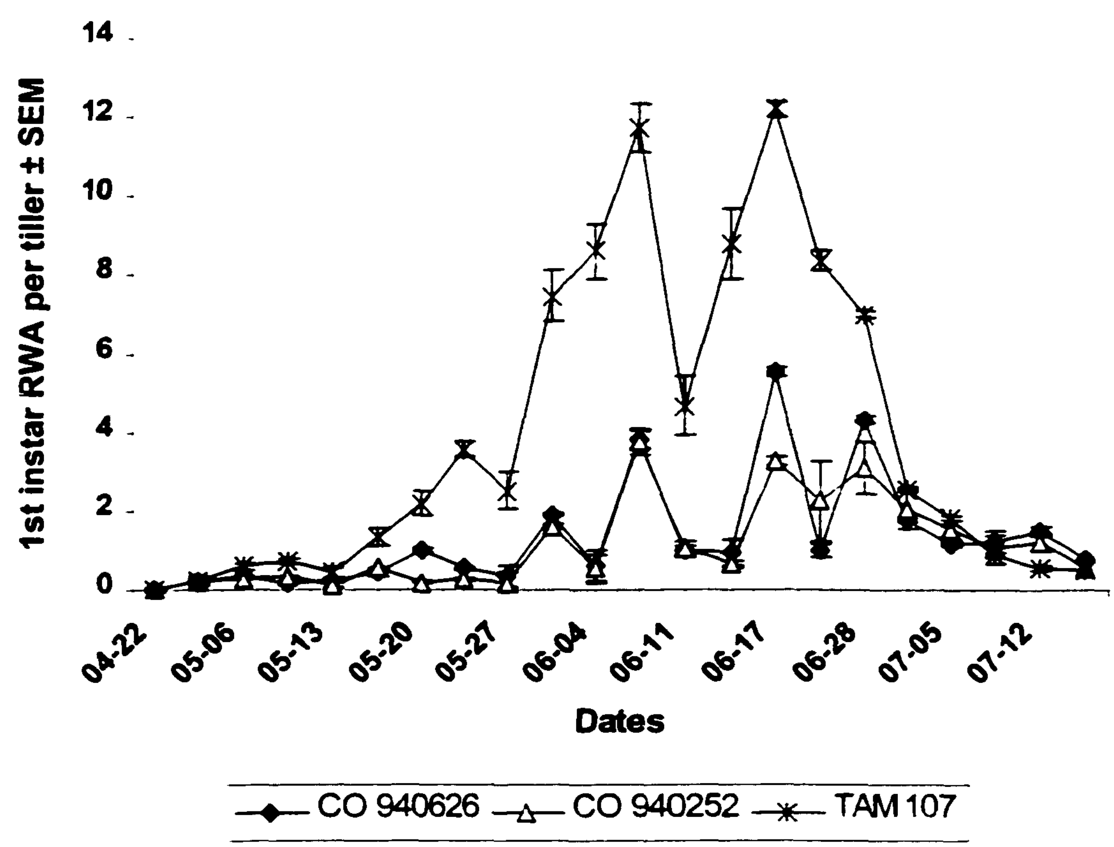

Fig 1.7. Mean ±SEM 1st Russian wheat aphids (RWA) per tiller collected from resistant and susceptible wheats. April-July 1996, averaged over 3 infestation levels. Agricultural Research Development and Education Center, Fort Collins, CO.

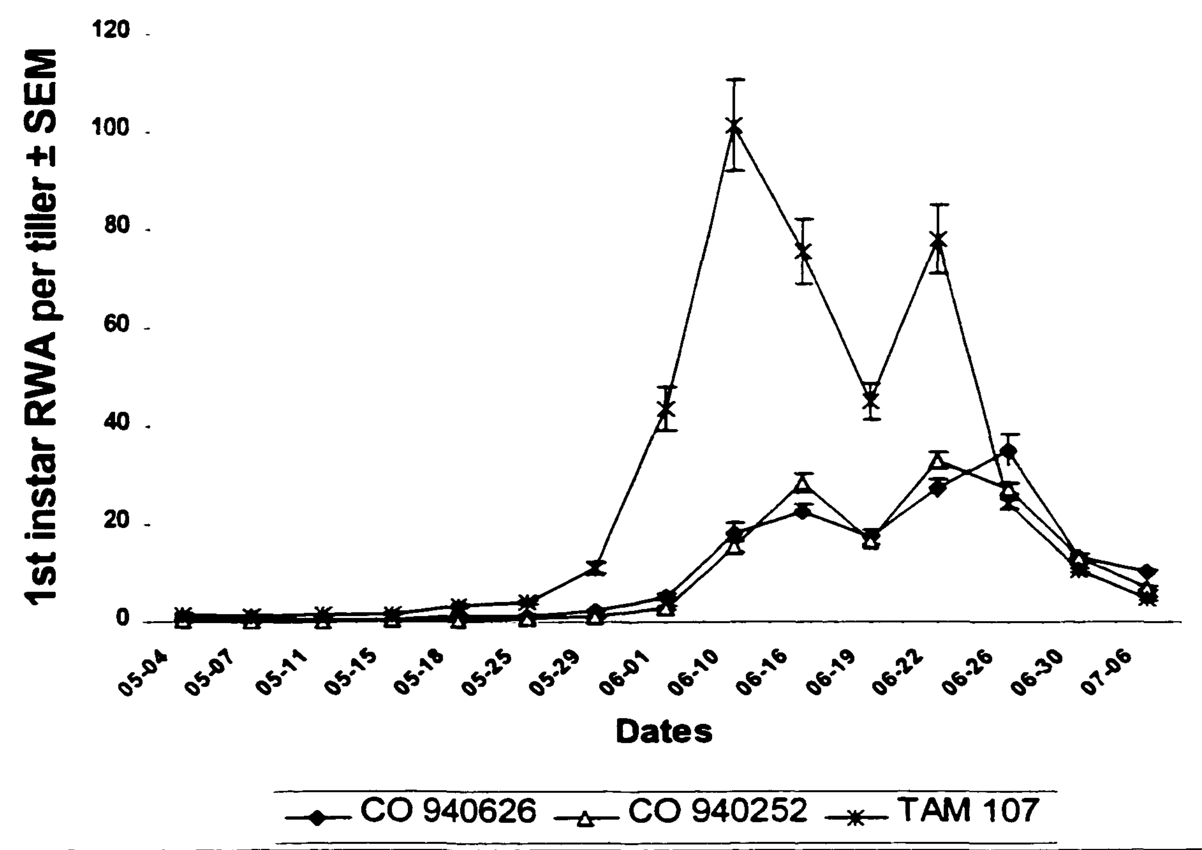

Fig 1.8. Mean (±SEM) 1st instar Russian wheat aphids (RWA) per tiller collected from resistant and susceptible wheats. April-July 1998, averaged over 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

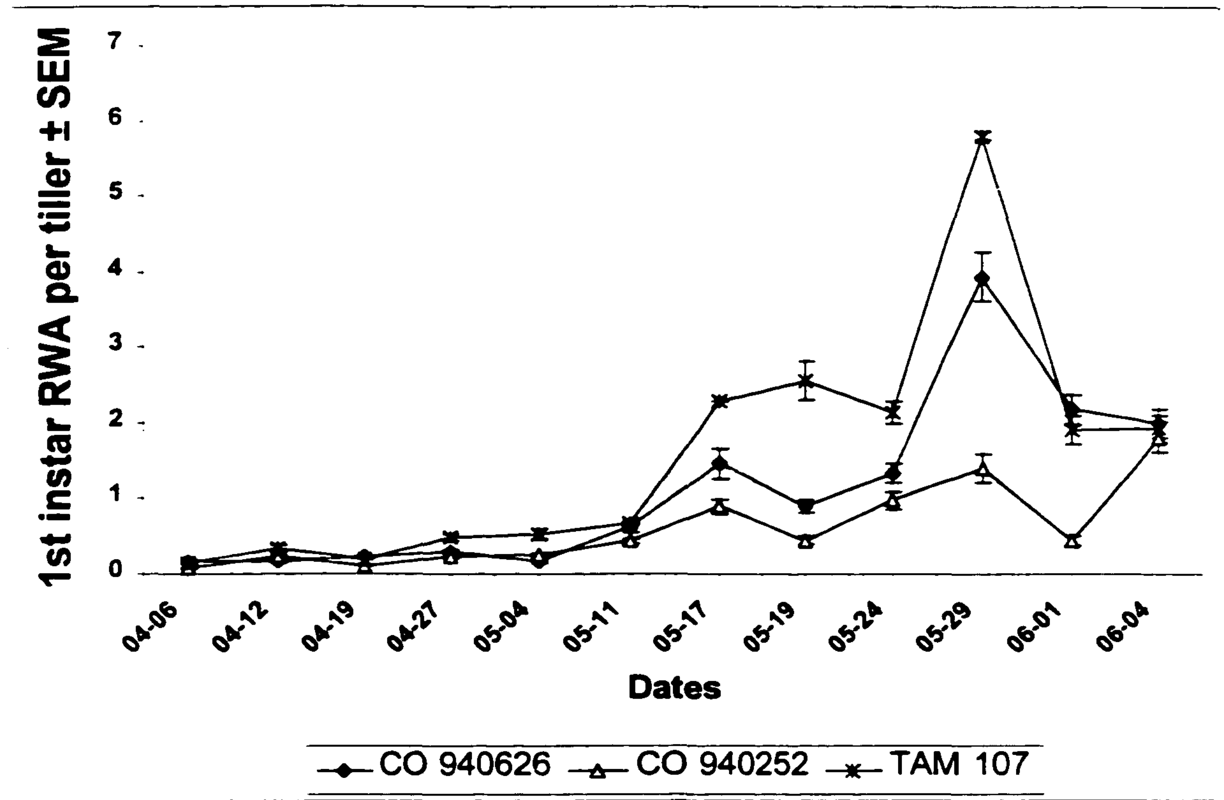

Fig 1.9. Mean (± SEM) 1st instar Russian wheat aphids (RWA) collected from resistant and susceptible wheats. April-June 1999, averaged over 3 infestation levels. Agricultural Research. Development and Education Center. Fort Collins. CO.

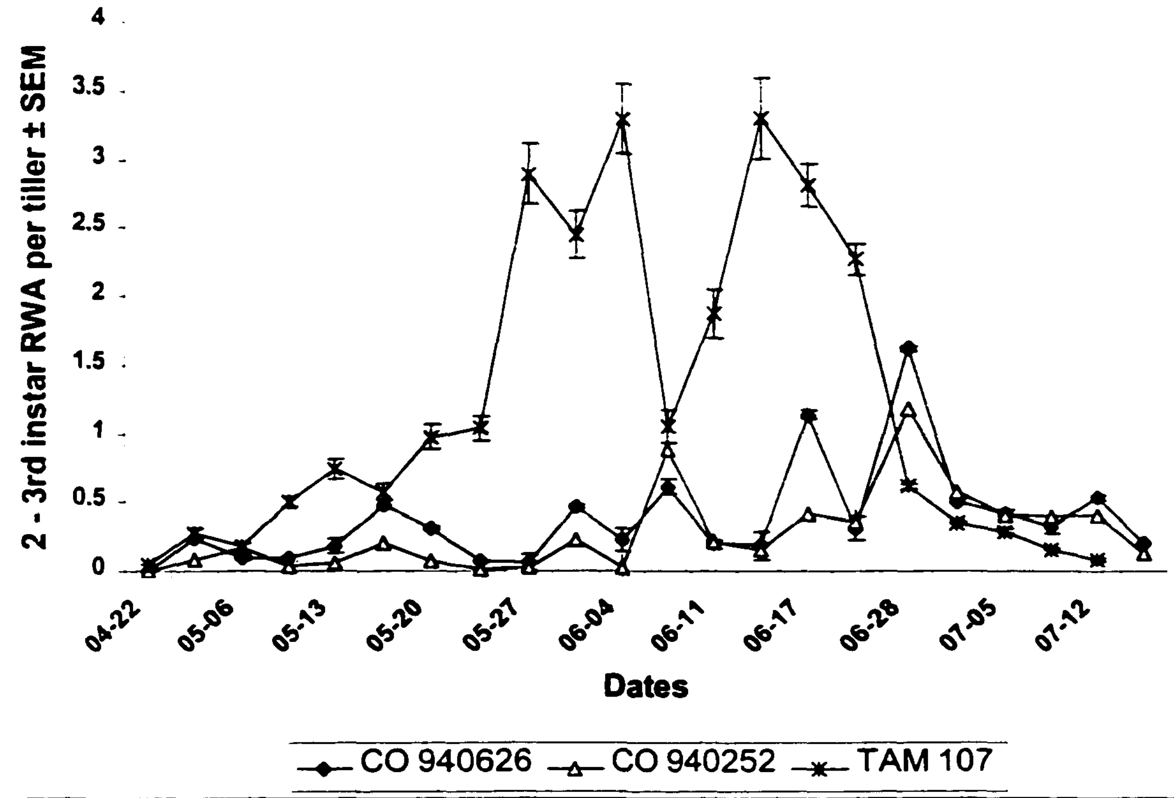

Fig 1.10. Mean (± SEM) 2nd -3rd instar Russian wheat aphids (RWA) per tiller collected from resistant and susceptible wheats, April-July 1996, averaged over 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

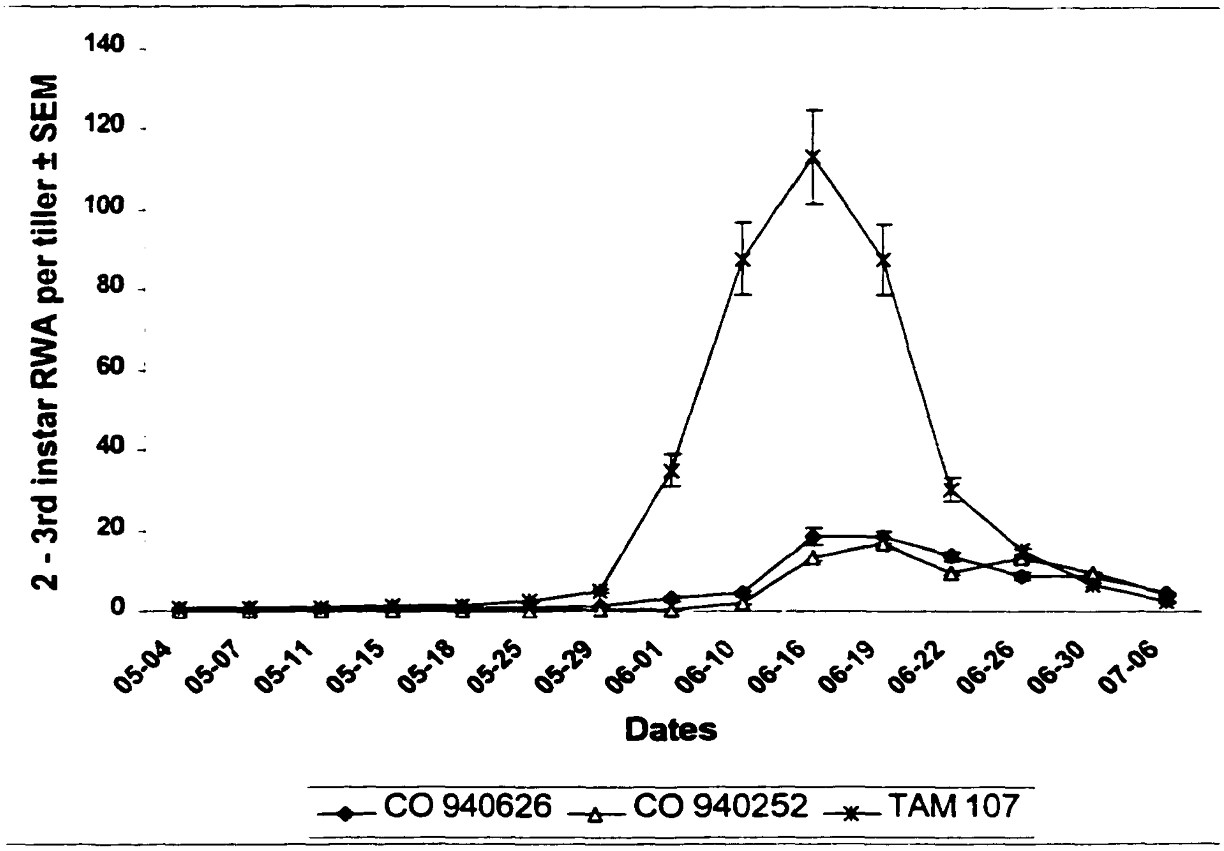

Fig 1.11. Mean (± SEM) 2nd -3rd instar Russian wheat aphids (RWA) per tiller collected from resistant and susceptible wheats, April-July 1998, averaged over 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

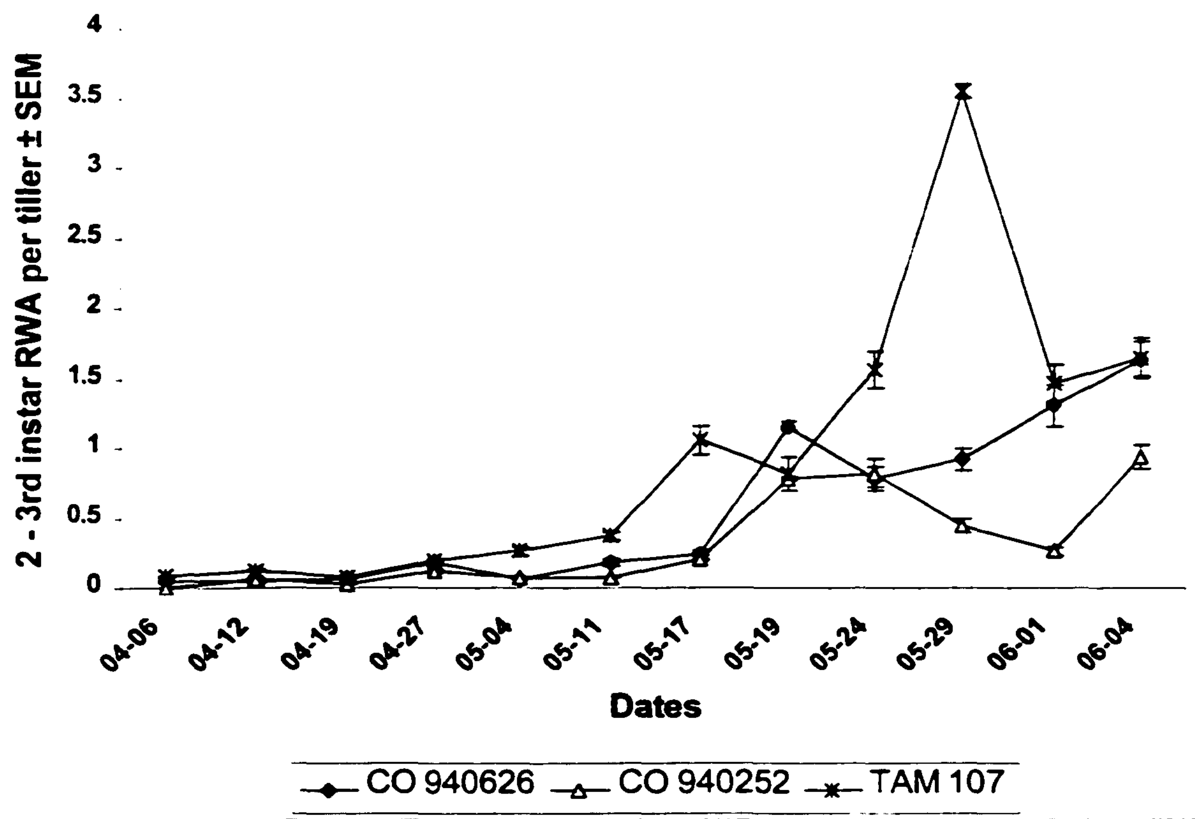

Fig 1.12. Mean (± SEM) 2nd - 3rd instar Russian wheat aphid (RWA) per tiller collected from resistant and susceptible wheats, April-June 1999, averaged over 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

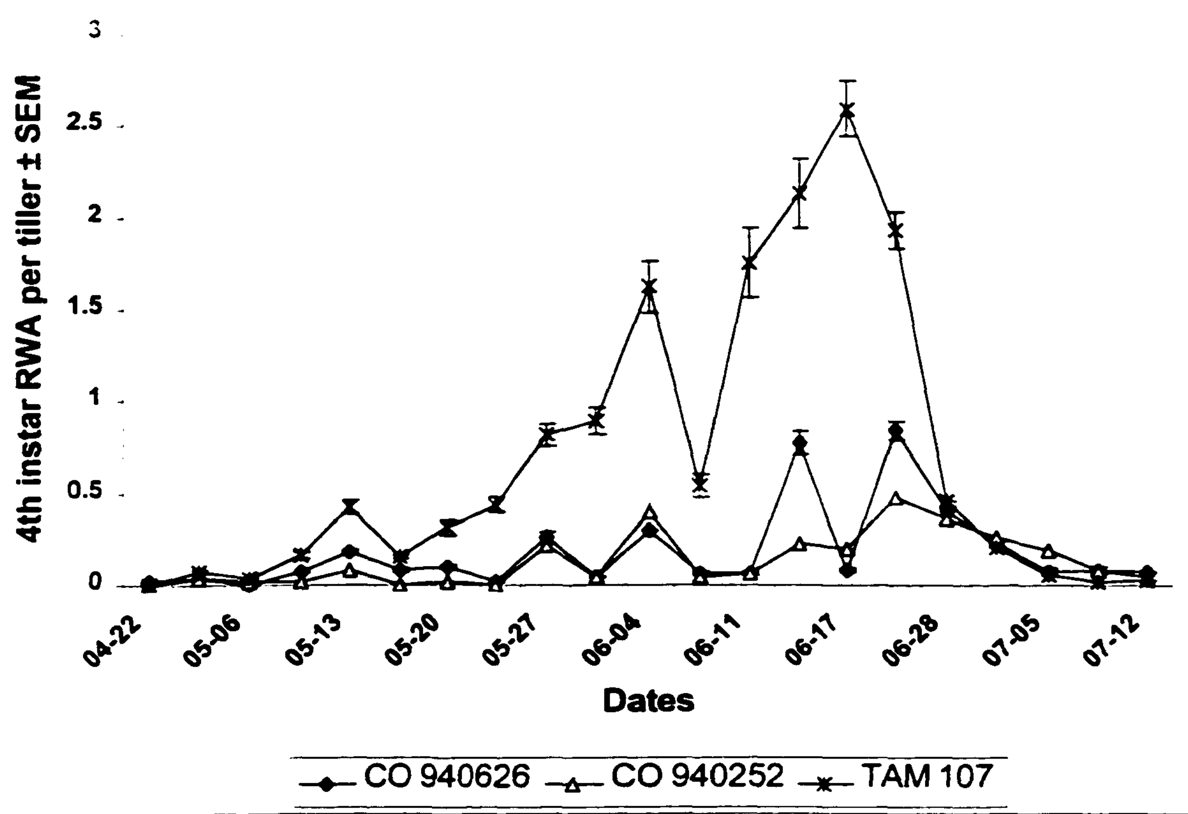

Fig 1.13. Mean (± SEM) 4th instar Russian wheat aphids (RWA) per tiller collected from resistant and susceptible wheats. April-July 1996, averaged over 3 infestation levels. Agricultural Research. Development and Education Center, Fort Collins, CO.

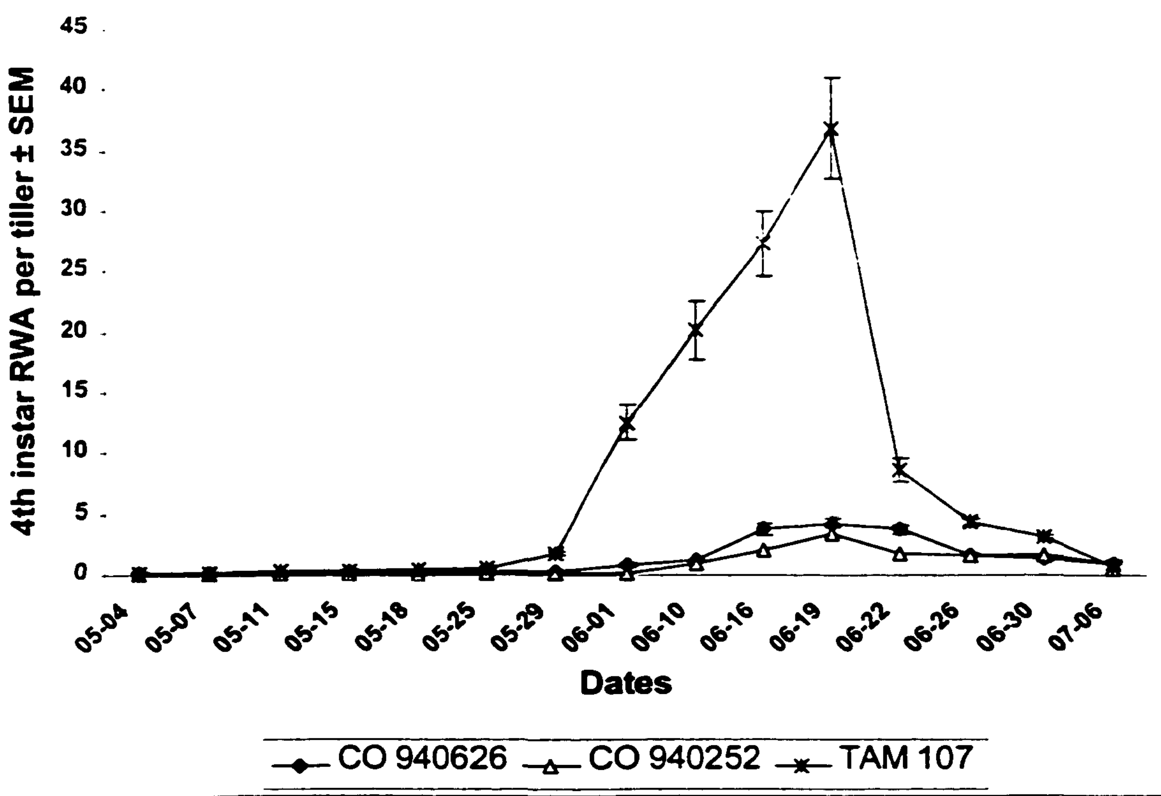

Fig 1.14. Mean (± SEM) 4th instar Russian wheat aphids (RWA) per tiller collected from resistant and susceptible wheats, April-July 1998, averaged over 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

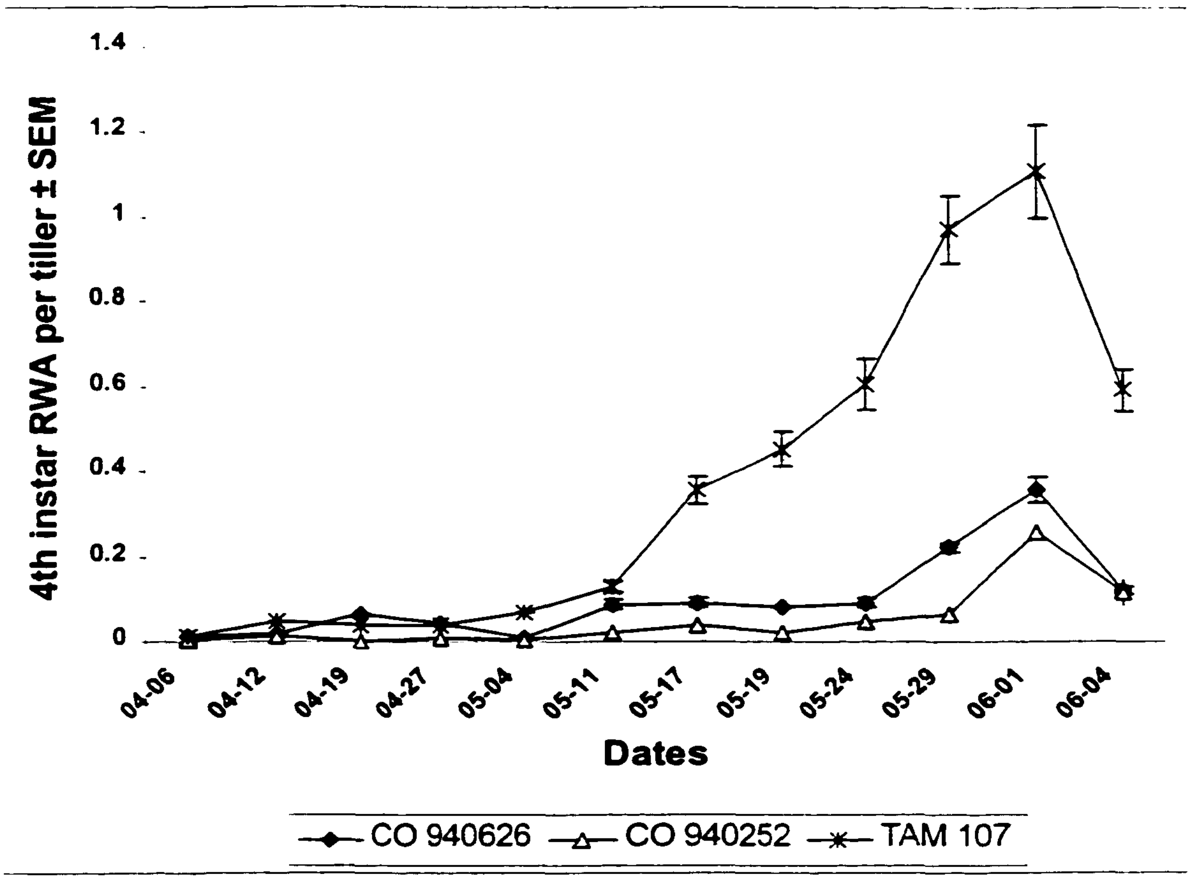

Fig 1.15. Mean (± SEM) 4th instar Russian wheat aphids (RWA) per tiller collected from resistant and susceptible wheats. April-June 1999, averaged over 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

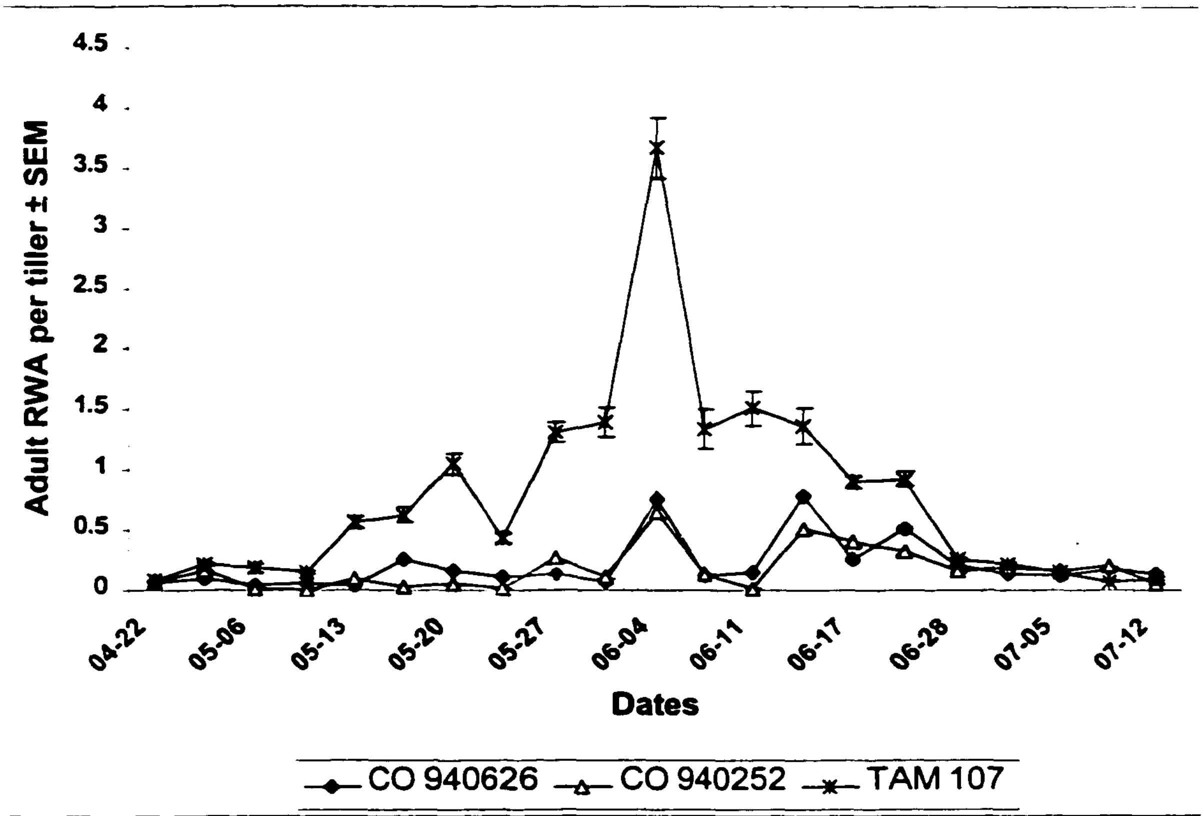

Fig 1.16. Mean (± SEM) adult Russian wheat aphids (RWA) per tiller collected from resistant and susceptible wheats, April-July 1996, averaged over 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

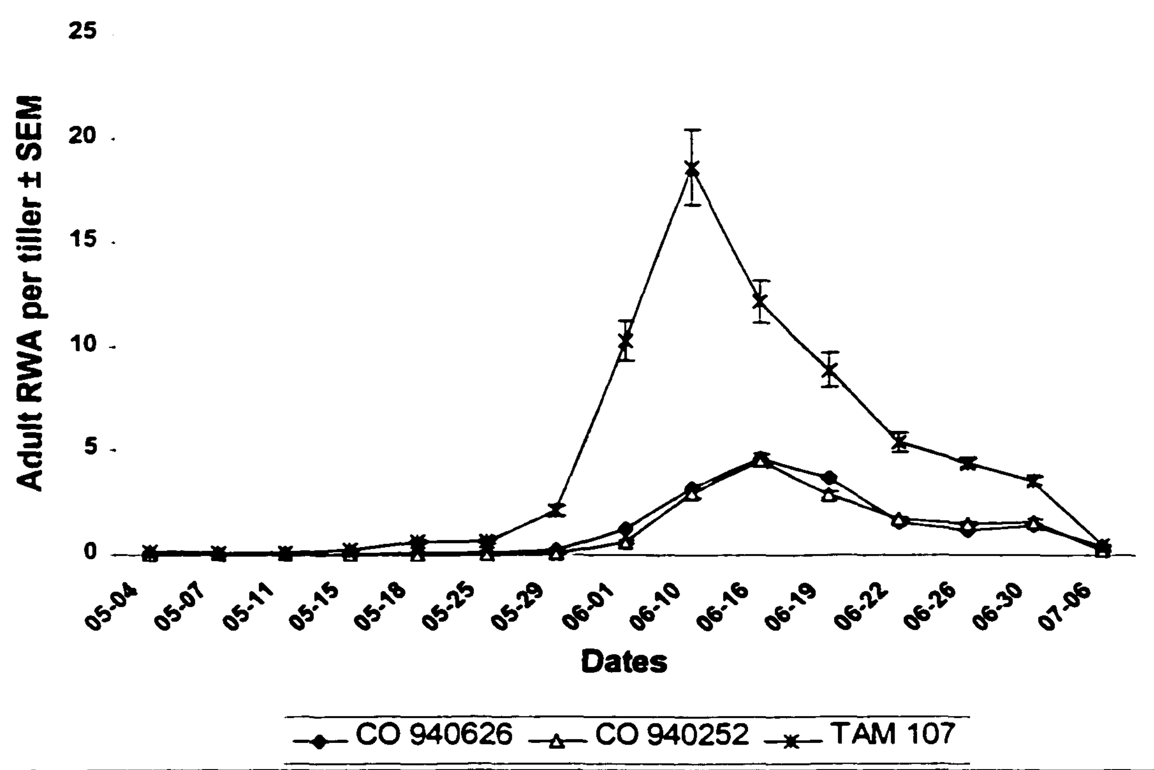

Fig 1.17. Mean (± SEM) adult Russian wheat aphids (RWA) per tiller collected from resistant and susceptible wheats. April-July 1998. averaged over 3 infestation levels. Agricultural Research. Development and Education Center. Fort Collins. CO.

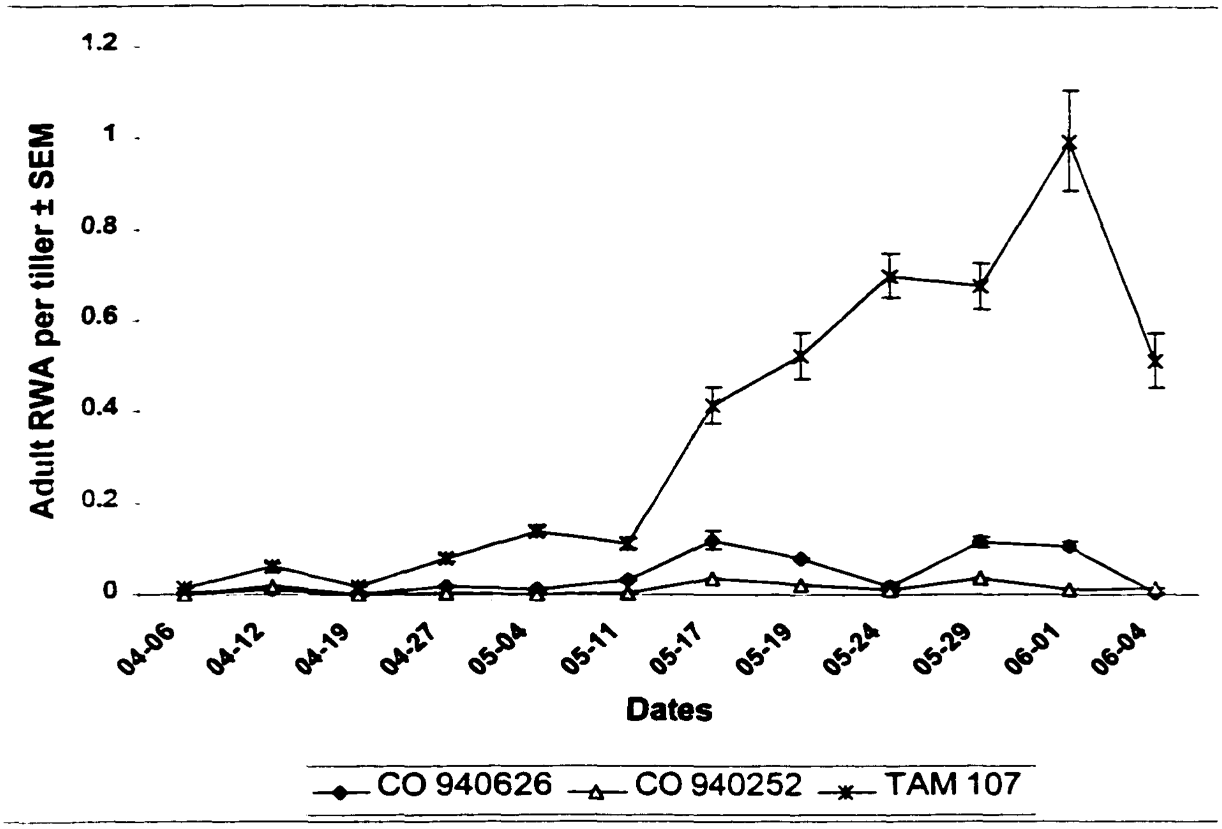

Fig 1.18. Mean (± SEM) adult Russian wheat aphids (RWA) per tiller collected from resistant and susceptible wheats, April-June 1999, averaged over 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes with different initial infestation density and aphid age structure.

Resistant wheats affected Russian wheat aphid age structure. The proportion of first instars in 1996 was affected by genotype (F = 6.58; df = 2, P= 0.0034), 1998 (F = 37.99; df = 2, P< 0.0001) and 1999 (F = 12.67; df = 2, P< 0.0001). The proportions of second and third instar, fourth instar and adult age classes also varied in their response to wheats genotypes in 1996: second-third instars (F = 2.05; df = 2, P= 0.1424), fourth instar (F = 8.37; df = 2, P= 0.0009), adults (F = 4.88; df = 2, P= 0.0127); in 1998: second-third instar (F = 10.58; df = 2, P= 0.0002), fourth instar (F = 55.09; df = 2, P< 0.0001), adult (F = 4.25; df = 2, P= 0.0213) and 1999 second-third instar (F = 0.34; df = 2, P= 0.7163), fourth instar (F = 1.80; df = 2, P= 0.1779) and adults (F = 6.93; df = 2, P= 0.0026) (Figs 1.20, 1.21 and 1.22). Differences were observed among the three years that can be explain in part by the density variations, since aphids collection in 1998 were almost seven fold greater comparing to 1996 and more than ten fold more abundant compared to 1999 as mentioned before. However, proportions of second-third, fourth instars and adults were clearly affected by wheat genotypes, as indicated by relatively high proportions of second-third, fourth instars and adults in TAM 107 compared with CO 940626, CO 940252 (Figs 1.19 , 1.20 and 1.21).

CO9400626 and CO940252 were similar in instar proportions in all three years (Tables 1.9-1.20), thus both resistant genes had similar effects on Russian wheat aphid age structure. However, orthogonal contrasts of the resistant wheats versus susceptible wheat in their effects on first instar proportion in 1996 (F = 11.33; df = 1, P= 0.0016) second-third instars (F = 1.04; df = 1, P= 0.3125), fourth instar (F = 14.41; df = 1, P=

0.0004) adult (F = 9.67; df = 1, P= 0.0033) in 1998, first instar (F = 37.61; df = 1, P< 0.0001), second-third instar (F = 12.63; df = 1, P= 0.0009) fourth instar (F = 59.77; df = 1, P< 0.0001), adult (F = 7.85; df = 1, P= 0.0073) and 1999 first instar (F = 6.67; df = 1, P= 0.0100), second-third instars (F = 1.29; df = 1, P= 0.2567), fourth instar (F = 45.75; df = 1, P< 0.0001) and adult (F =69.82, df = 1, P<0.0001) were significant except for the second-third instar comparisons in 1996 and 1999 for unknown reasons. The difference in age classes structure is an expression of antibiosis by both Dn4 and Dn6. Although Hawley (1997) concluded that Dn4 confers mostly tolerance to Russian wheat aphid under lab conditions, these field results indicate antibiosis expressed by Dn4. Differences in results could be due to the experiment methods and experimental conditions.

In addition, some interactions of wheat genotypes and infestation levels were observed (Figs 1.22, 1.23 and 1.24). As initial infestation level increased first instar proportions tended to decline in contrast to fourth instar and adult proportions. This trend might be more clear with higher initial infestations. However, no significant interactions were observed for age structure and initial infestation level during the 1996 season as well as some age classes in 1998 and 1999 (Tables 1.9-1.20).

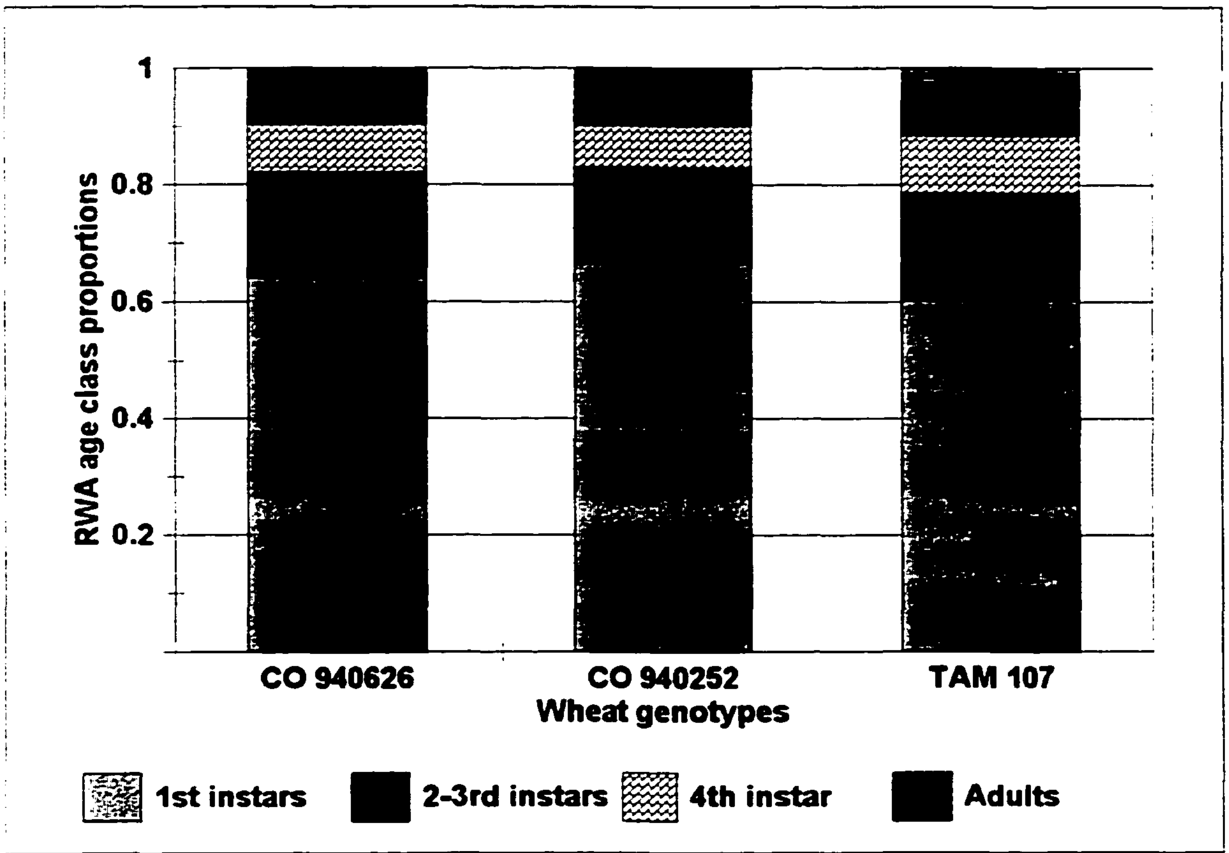

Fig 1.19. Age class structure of Russian wheat aphids (RWA) collected in 1996 from 3 wheats, differing in aphid resistance, averaged over 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

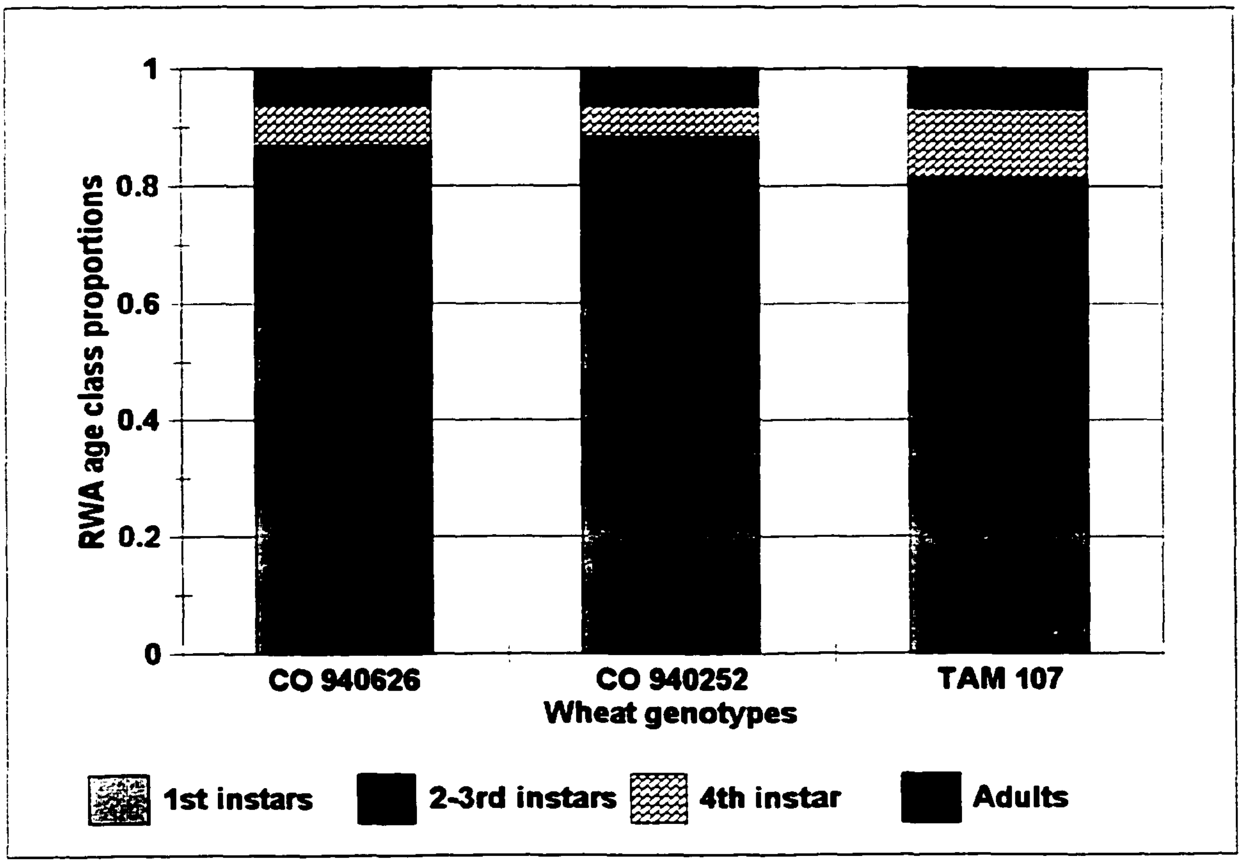

Fig 1.20. Age class structure of Russian wheat aphids (RWA) collected in 1998 from 3 wheats, differing in aphid resistance, averaged over 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

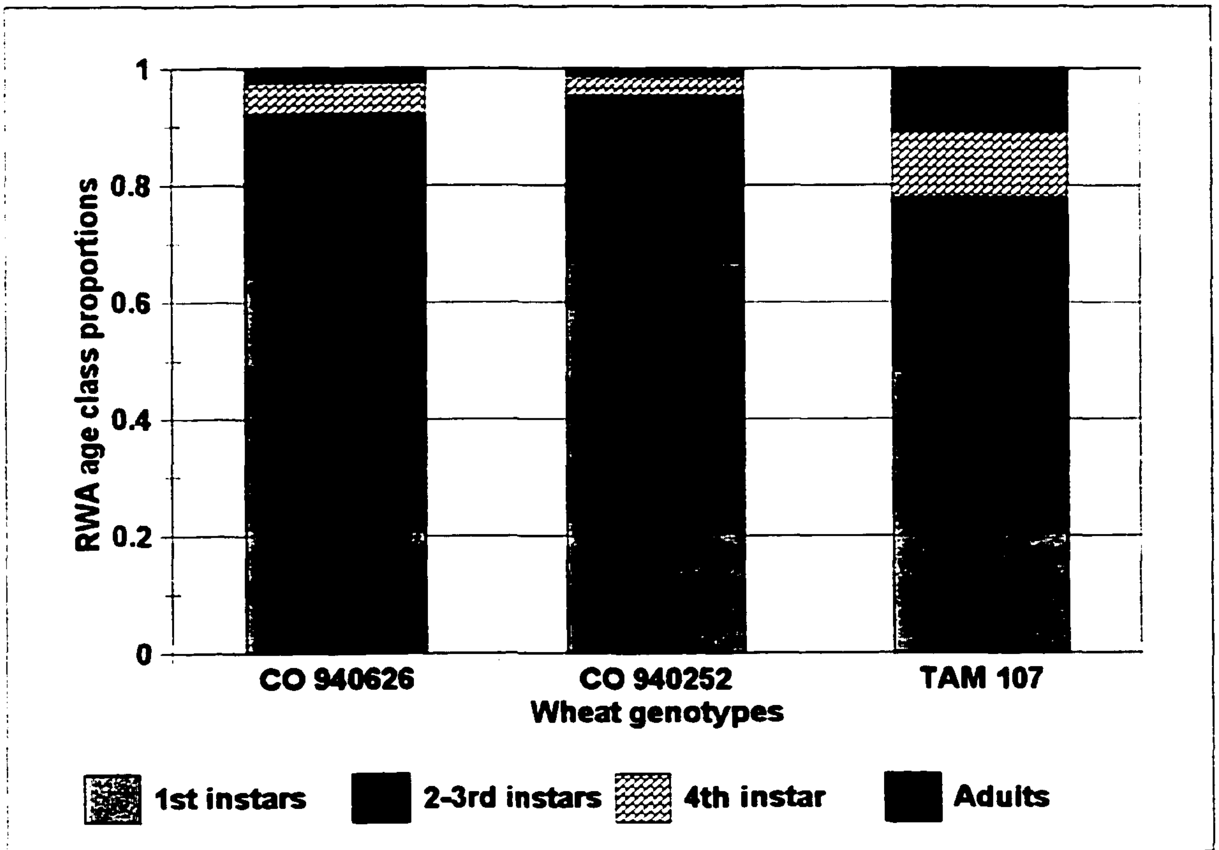

Fig 1.21. Age class structure of Russian wheat aphids (RWA) collected in 1999 from 3 wheats differing in aphid resistance. averaged over 3 infestation levels. Agricultural Research. Development and Education Center. Fort Collins. CO.

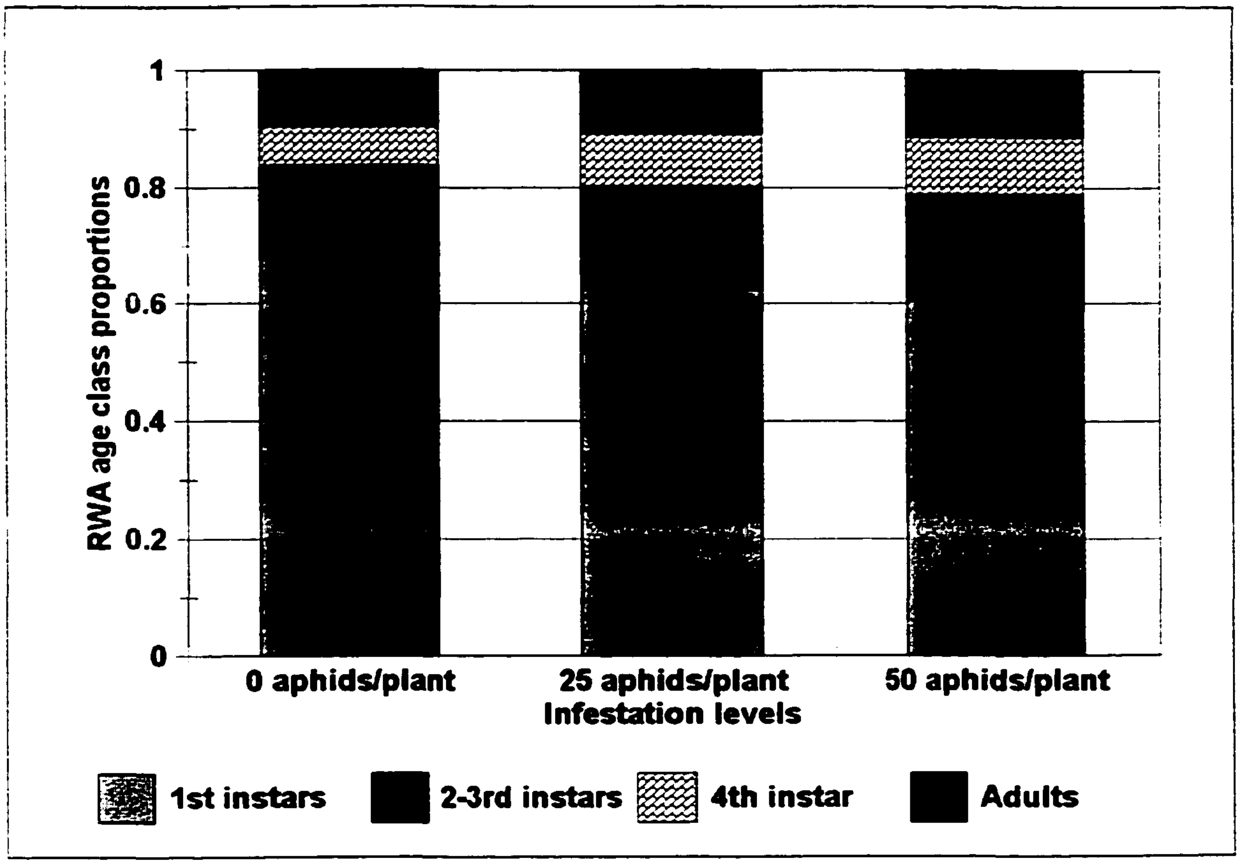

Fig 1.22. Age class structure of Russian wheat aphids (RWA) collected in 1996 subsequent to 3 levels of infestation. averaged over 3 wheats. Agricultural Research. Development and Education Center. Fort Collins. CO.

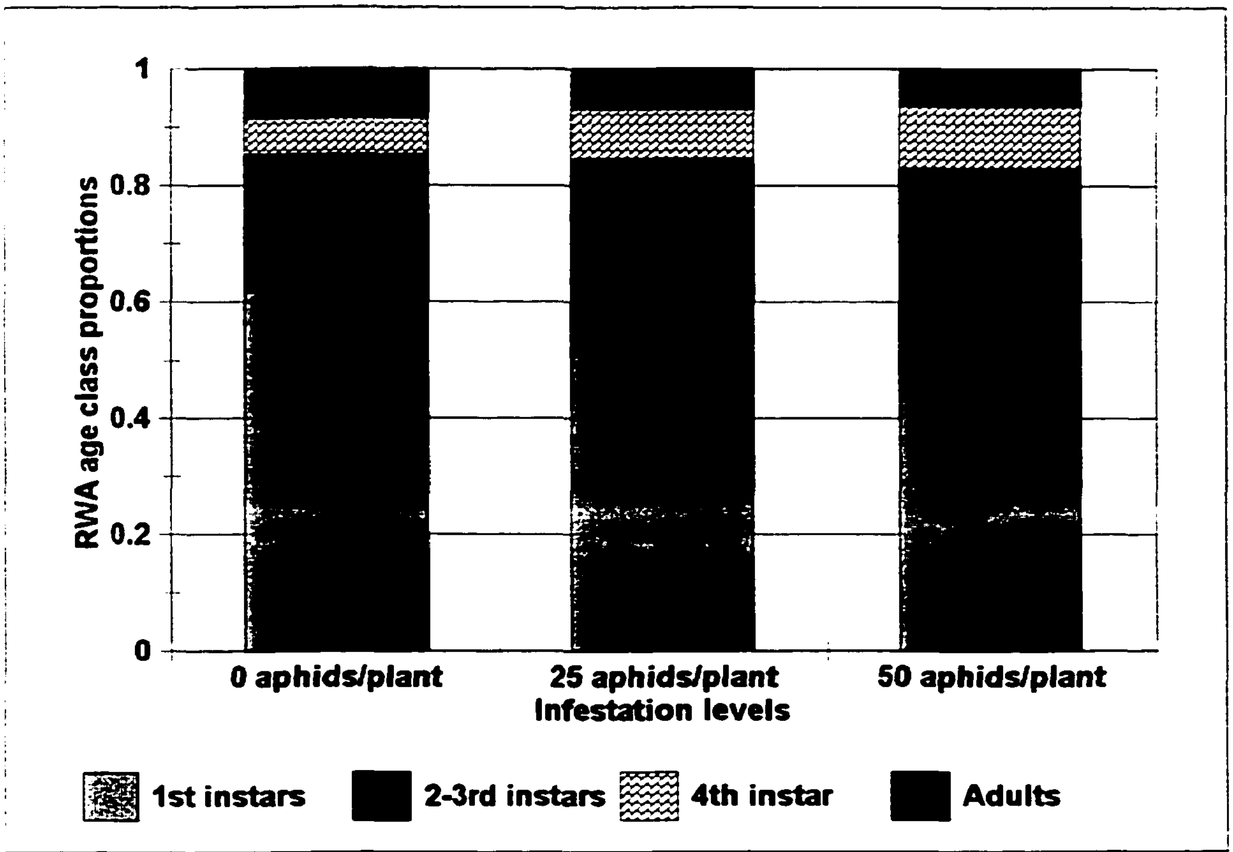

Fig 1.23. Age class structure of Russian wheat aphids (RWA) collected in 1998 subsequent to 3 levels of infestation. averaged over 3 wheats. Agricultural Research. Development and Education Center. Fort Collins. CO.

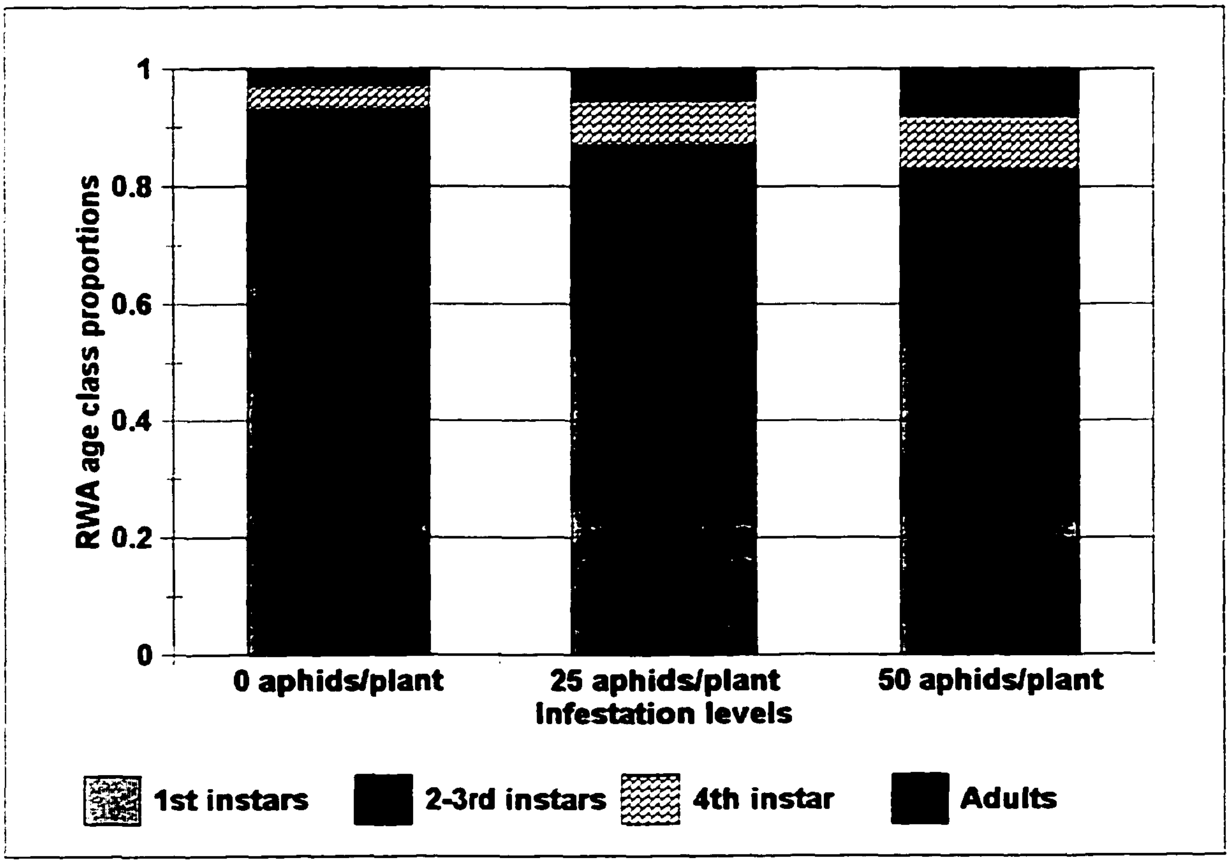

Fig 1.24. Age class structure of Russian wheat aphids (RWA) collected in 1999 subsequent to 3 levels of infestation, averaged over 3 wheats. Agricultural Research. Development and Education Center, Fort Collins, CO.

Table 1.9. Proportion (± SEM) of first instar Russian wheat aphids sampled April-July 1996 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins. CO.

Wheat genotypes	**Infestation Levels [1]**		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	0.694 ± 0.0a	0.650 ± 0.0ab	0.617 ± 0.0a
CO 940252	0.737 ± 0.0a	0.671 ± 0.0a	0.642 ± 0.0a
TAM 107	0.643 ± 0.0a	0.611 ± 0.0b	0.594 ± 0.0a
$Dunn_{0.05}$ / $LSD_{0.05}$	0.1395	0.0514	0.0526
F- value	1.34	3.33	1.76
P > *F*	0.3268	0.0422	0.2019

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if P > *F* < 0.05 or $Dunn_{0.05}$ in P > *F* > 0.05.
[1]Number of Russian wheat aphid originally infested / plant on November 8, 1995.

Table 1.10. Proportion (± SEM) of second-third instar Russian wheat aphids sampled April-July 1996 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	**Infestation Levels [1]**		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	0.168 ± 0.0a	0.174 ± 0.0a	0.182 ± 0.0a
CO 940252	0.121 ± 0.0a	0.158 ± 0.0a	0.172 ± 0.0a
TAM 107	0.167 ± 0.0a	0.176 ± 0.0a	0.181 ± 0.0a
$Dunn_{0.05}$	0.0992	0.0415	0.0489
F- value	1.30	1.42	0.38
P > *F*	0.3400	0.2974	0.8932

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if P > *F* < 0.05 or $Dunn_{0.05}$ in P > *F* > 0.05.
[1]Number of Russian wheat aphid originally infested / plant on November 8, 1995.

Table 1.11. Proportion (± SEM) of fourth instar Russian wheat aphids sampled April-July 1996 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation Levels [1]		
	0 aphids/plant	25 aphids/plant	50 aphids/plant
CO 940626	0.059 ± 0.0a	0.082 ± 0.0ab	0.098 ± 0.0a
CO 940252	0.050 ± 0.0a	0.078 ± 0.0b	0.078 ± 0.0a
TAM 107	0.075 ± 0.0a	0.100 ± 0.0a	0.107 ± 0.0a
$Dunn_{0.05}$	0.0377	0.029	0.0323
F- value	1.45	0.97	1.55
P > *F*	0.2880	0.4999	0.2546

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.

[1]Number of Russian wheat aphid originally infested / plant on November 8, 1995.

Table 1.12. Proportion (± SEM) of adult Russian wheat aphids sampled April-July 1996 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation Levels [1]		
	0 aphids/plant	25 aphids/plant	50 aphids/plant
CO 940626	0.076 ± 0.0a	0.093 ± 0.0a	0.100 ± 0.0a
CO 940252	0.089 ± 0.0a	0.092 ± 0.0a	0.107 ± 0.0a
TAM 107	0.113 ± 0.0a	0.110 ± 0.0a	0.117 ± 0.0a
$Dunn_{0.05}$	0.0527	0.0321	0.0267
F- value	0.84	2.36	0.90
P > *F*	0.5763	0.1054	0.5444

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.

[1]Number of Russian wheat aphid originally infested / plant on November 8, 1995.

Table 1.13. Proportion (± SEM) of first instar Russian wheat aphids sampled April-July 1998 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation Levels [1]		
	0 aphids/plant	25 aphids/plant	50 aphids/plant
CO 940626	0.633 ± 0.0a	0.610 ± 0.0a	0.519 ± 0.0b
CO 940252	0.621 ± 0.0a	0.592 ± 0.0a	0.592 ± 0.0a
TAM 107	0.625 ± 0.0a	0.460 ± 0.0b	0.398 ± 0.0c
$Dunn_{0.05}$ / $LSD_{0.05}$	0.078	0.0371	0.0482
F- value	0.89	16.37	12.56
P > F	0.5449	0.0001	0.0003

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if P > F < 0.05 or $Dunn_{0.05}$ in P > F > 0.05.
[1]Number of Russian wheat aphid originally infested/plant on February 27, 1998.

Table 1.14. Proportion (± SEM) of second-third instar Russian wheat aphids sampled April-July 1998 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation Levels [1]		
	0 aphids/plant	25 aphids/plant	50 aphids/plant
CO 940626	0.215 ± 0.0a	0.277 ± 0.0b	0.334 ± 0.0b
CO 940252	0.254 ± 0.0a	0.293 ± 0.0b	0.290 ± 0.0b
TAM 107	0.212 ± 0.0a	0.354 ± 0.0a	0.413 ± 0.0a
$LSD_{0.05}$	0.0585	0.03	0.0458
F- value	3.17	7.31	6.10
P > F	0.0486	0.0029	0.0056

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if P > F < 0.05 or $Dunn_{0.05}$ in P > F > 0.05.
[1]Number of Russian wheat aphid originally infested/plant on February 27, 1998.

Table 1.15. Proportion (± SEM) of fourth instar Russian wheat aphids sampled April-July 1998 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	**Infestation Levels** [1]		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	0.067 ± 0.0a	0.056 ± 0.0b	0.078 ± 0.0b
CO 940252	0.055 ± 0.0a	0.047 ± 0.0b	0.053 ± 0.0c
TAM 107	0.068 ± 0.0a	0.099 ± 0.0a	0.122 ± 0.0a
$Dunn_{0.05}$ /$LSD_{0.05}$	0.0236	0.0164	0.016
F- value	0.93	9.07	14.04
P > *F*	0.5228	0.0012	0.0002

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.

[1]Number of Russian wheat aphid originally infested/plant on February 27, 1998.

Table 1.16. Proportion (± SEM) of adult Russian wheat aphids sampled April-July 1998 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	**Infestation Levels** [1]		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	0.083 ± 0.0a	0.055 ± 0.0b	0.067 ± 0.0a
CO 940252	0.068 ± 0.0a	0.066 ± 0.0b	0.063 ± 0.0a
TAM 107	0.093 ± 0.0a	0.085 ± 0.0a	0.065 ± 0.0a
$Dunn_{0.05}$ /$LSD_{0.05}$	0.046	0.0126	0.0165
F- value	0.66	4.96	1.12
P > *F*	0.6987	0.0118	0.4210

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.

[1]Number of Russian wheat aphid originally infested/plant on February 27, 1998.

Table 1.17. Proportion (± SEM) of first instar Russian wheat aphids sampled April-June 1999 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	**Infestation Level [1]**		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	0.304 ± 0.0a	0.538 ± 0.0a	0.576 ± 0.0a
CO 940252	0.162 ± 0.0ab	0.548 ± 0.0a	0.589 ± 0.0a
TAM 107	0.204 ± 0.0b	0.593 ± 0.0a	0.454 ± 0.0b
$Dunn_{0.05}$ / $LSD_{0.05}$	0.1252	0.1277	0.0831
F- value	2.69	1.24	5.30
P > *F*	0.0704	0.2912	0.0057

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.

[1]Number of Russian wheat aphid originally infested/plant on March 15, 1999.

Table 1.18. Proportion (± SEM) of second-third instar Russian wheat aphids sampled April-June 1999 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	**Infestation Levels [1]**		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	0.047 ± 0.0a	0.200 ± 0.0ab	0.259 ± 0.0a
CO 940252	0.018 ± 0.0a	0.153 ± 0.0b	0.211 ± 0.0a
TAM 107	0.025 ± 0.0a	0.240 ± 0.2a	0.222 ± 0.0a
$Dunn_{0.05}$ / $LSD_{0.05}$	0.0334	0.0691	0.0567
F- value	2.41	2.47	2.99
P > *F*	0.0921	0.0871	0.0525

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.

[1]Number of Russian wheat aphid originally infested/plant on March 15, 1999.

Table 1.19. Proportion (± SEM) of fourth instar Russian wheat aphids sampled April-June 1999 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation Levels [1]		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	0.002 ± 0.0a	0.044 ± 0.0b	0.046 ± 0.0b
CO 940252	0.008 ± 0.0a	0.013 ± 0.0c	0.019 ± 0.0c
TAM 107	0.007 ± 0.0a	0.066 ± 0.0a	0.088 ± 0.0a
$Dunn_{0.05}$ / $LSD_{0.05}$	0.0173	0.0192	0.0194
F- value	1.42	1.80	30.63
$P > F$	0.2438	0.0001	0.0001

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.
[1]Number of Russian wheat aphid originally infested/plant on March 15, 1999.

Table 1.20. Proportion (± SEM) of adult Russian wheat aphids sampled April-June 1999 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation Levels [1]		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	0.000 ± 0.0a	0.015 ± 0.0b	0.026 ± 0.0b
CO 940252	0.001 ± 0.0a	0.017 ± 0.0b	0.008 ± 0.0b
TAM 107	0.017 ± 0.0a	0.074 ± 0.0a	0.100 ± 0.0a
$Dunn_{0.05}$ / $LSD_{0.05}$	0.0281	0.0279	0.022
F- value	0.78	11.36	37.90
$P > F$	0.4615	0.0001	0.0001

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.
[1]Number of Russian wheat aphid originally infested/plant on March 15, 1999.

Natural enemy interaction with wheat genotypes and infestation levels.

Natural enemy observations indicated less parasitoid activity in 1996 and 1999 than in 1998 (Table 1.21). Wheat genotype affected parasitoid activity in all three years (Table 1.21). Although both resistant wheats had a flat leaves, more mummies were collected from TAM 107 (Table 1.21). Factors other than leaf structure thus affected parasitoid mummy abundance. Brewer et al. (1998) reported that uncurled barley leaves did not provide a better environment for *D. rapae*. The relatively large collections of *D. rapae* parasitoid mummies in 1998 might be explained by two facts. In 1998, the study site was adjacent to two rows of canola plants, which are attractive to this parasitoid (M. Antolin, Department of Biology, Colorado State University, personal communication). Secondly, there might have been functional response to the high density of Russian wheat aphids during the 1998 season. Initial infestation levels showed a significant interaction with wheat genotypes on parasitoid mummies in 1996 and 1998 (Tables 1.22,1.23). In 1999 no interaction was observed between infestation level and wheat genotype, perhaps due to the relative low density of Russian wheat aphids.

According to Mohamed (1995), predators followed Russian wheat aphid trends. Messina et al. (1997) concluded that predators had a better chance in capturing the aphids on unrolled grass leaves than rolled grass leaves. However, in this study fewer predators were collected by sweep net in 1998 and 1999 than 1996 (Tables 1.25-1.27). The sampling method used in this study prevented analysis of the relationship of predators with wheat genotypes and infestations levels.

Table 1.21. Mean number (± SEM) of parasitoid mummies per tiller sampled 1996. 1998, 1999 on 3 wheats, infested at 3 levels. Agricultural Research, Development and Education Center. Fort Collins, CO.

Wheat genotypes	**Mummies per tiller**		
	Years		
	1996 [1]	**1998** [2]	**1999** [3]
CO 940626	0.02 ± 0.0a	0.04 ± 0.0b	0.01 ± 0.0ab
CO 940252	0.00 ± 0.0b	0.04 ± 0.0b	0.01 ± 0.0b
TAM 107	0.02 ± 0.0a	0.15 ± 0.0a	0.03 ± 0.0a
$Dunn_{0.05}$ / $LSD_{0.05}$	0.0071	0.0396	0.0223
F- value	9.33	17.67	2.70
P > *F*	0.0001	0.0001	0.0680

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.

[1] Russian wheat aphid infestation on November 8, 1996.

[2] Russian wheat aphid infestation on February 27, 1998.

[3] Russian wheat aphid infestation on March 15, 1999.

Table 1.22. Mean number (± SEM) of parasitoid mummies *D. rapae* per tiller sampled April-July 1996 on 3 wheats at 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation Levels [1]		
	0 aphids/plant	25 aphids/plant	50 aphids/plant
CO 940626	0.02 ± 0.0a	0.02 ± 0.0a	0.01 ± 0.0b
CO 940252	0.01 ± 0.0b	0.01 ± 0.0b	0.00 ± 0.0b
TAM 107	0.00 ± 0.0b	0.03 ± 0.0b	0.04 ± 0.0a
$LSD_{0.05}$	0.0103	0.0127	0.0144
F- value	7.08	5.53	11.66
P > *F*	0.0010	0.0043	0.0001

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.

[1]Number of Russian wheat aphid originally infested/plant on November 8, 1996.

Table 1.23. Mean number (± SEM) of parasitoid mummies *D. rapae* per tiller sampled April-July 1998 on 3 wheats at 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation Levels [1]		
	0 aphids/plant	25 aphids/plant	50 aphids/plant
CO 940626	0.01 ± 0.0a	0.05 ± 0.0a	0.07 ± 0.0b
CO 940252	0.01 ± 0.0a	0.05 ± 0.0a	0.06 ± 0.0b
TAM 107	0.05 ± 0.0a	0.11 ± 0.0a	0.28 ± 0.0a
$Dunn_{0.05}$ /$LSD_{0.05}$	0.0435	0.0755	0.1048
F- value	2.81	2.84	10.33
P > *F*	0.0619	0.0603	0.0001

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.

[1] Number of Russian wheat aphid originally infested/plant on February 27, 1998.

Table 1.24. Mean number (± SEM) of parasitoid mummies *D. rapae* per tiller sampled April-Jun 1999 on 3 wheats at 3 infestation levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	**Infestation Levels** [1]		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	0.00 ± 0.0a	0.01 ± 0.0a	0.03 ± 0.0a
CO 940252	0.00 ± 0.0a	0.02 ± 0.0a	0.01 ± 0.0a
TAM 107	0.03 ± 0.0a	0.03 ± 0.0a	0.04 ± 0.0a
$Dunn_{0.05}$ / $LSD_{0.05}$	0.0421	0.032	0.0511
F- value	1.40	1.74	0.84
$P > F$	0.2487	0.1787	0.4326

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.

[1]Number of Russian wheat aphid originally infested/plant on March 15, 1999.

Table 1.25. Predators of Russian wheat aphid collected from the host plants using a sweep net. Agricultural Research, Development and Education Center. Fort Collins, CO 1996.

Sampling dates	Predators per one sweep		
	Hippodamia convergens	*Coccinella septempunctata*	*Orius* sp
04-22-96	0	0	0
05-06-96	0	0	0
05-13-96	0	0	0
05-20-96	0	0	0
05-27-96	0	0	0
06-04-96	0	0	1
06-11-96	0	0	1
06-13-96	0	0	0
06-17-96	0	0	0
06-24-96	1	0	0
06-28-96	0	0	0
07-05-96	1	0	0
07-08-96	1	0	0
07-10-96	1	0	0
Total	4	0	2

Table 1.26. **Predators of Russian wheat aphid collected from the host plants using a sweep net. Agricultural Research, Development and Education Center, Fort Collins, CO 1998.**

Sampling dates	**Predators per one sweep**		
	Hippodamia convergens	*Coccinella septempunctata*	*Orius* sp
05-04-98	0	0	0
05-07-98	0	0	0
05-11-98	0	0	0
05-15-98	0	0	0
05-18-98	0	0	0
05-26-98	0	0	0
05-29-98	0	0	1
06-01-98	0	0	0
06-10-98	0	0	1
06-16-98	0	0	0
06-19-98	0	0	0
06-22-98	0	0	0
06-26-98	0	0	0
06-30-98	1	1	0
07-06-98	0	0	0
Total	1	1	2

Table 1.27. Predators of Russian wheat aphid collected from the host plants using a sweep net. Agricultural Research, Development and Education Center, Fort Collins, CO 1999.

Sampling dates	**Predators per one sweep**		
	Hippodamia convergens	*Coccinella septempunctata*	*Orius* sp
04-06-99	0	0	0
04-12-99	0	0	0
04-19-99	0	0	0
04-27-99	0	0	0
05-04-99	0	0	0
05-11-99	0	0	0
05-17-99	0	0	0
05-19-99	0	0	0
05-24-99	0	0	0
05-29-99	0	0	0
06-01-99	0	0	0
06-04-99	0	0	0
Total	0	0	0

Effects of Russian wheat aphid on yield components.

Grain yield and quantity based on number of spikes, total seed weight (g), 1000-seed weight (g) and grain protein content were similar among wheats at the low, medium and high levels of infestation in all years (Tables 1.28 - 1.38). However, 1000-seed weight was reduced in TAM 107 at high infestation level in 1996 (Table 1.29), at the medium and high infestation level in 1998 and at high infestation level in 1999 (Tables 1.30, 1.34,1.38). Both CO 940626 and TAM 107 1000-seed weights were lower at the high infestation level (Tables 1.34 and 1.38). This shouldn't be surprising because both CO 940626 and TAM 107 are genetically close. Since CO 940626 was back crossed to TAM 107 five times, indicating that 95% of TAM 107 genetic bases were transferred to CO 940626. Grain protein was higher in TAM 107 than in the resistant wheats at the medium infestation level in 1998 and 1999, which could be due to reduced test weight (Tables 1.35 and 1.39). High grain protein level might be a genotypic difference or a response to the stress from aphid feeding. Resistant wheats were similar in yield and quality in all years, except for grain protein in 1999 at high infestation level (Table 1.39).

Table 1.28. Mean number of wheat spikes per meter (± SEM) sampled in 1996 on 3 wheats varying in resistance to Russian wheat aphid, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation levels [1]		
	0 aphids/plant	25 aphids/plant	50 aphids/plant
CO 940626	98.6 ± 18.1a	170.2 ± 24.5a	165.0 ± 24.7a
CO 940252	103.8 ± 30.9a	165.3 ± 36.3a	168.1 ± 15.3a
TAM 107	95.8 ± 17.8a	164.5 ± 30.9a	159.3 ± 24.8a
$Dunn_{0.05}$	64.821	128.153	117.238
F- value	1.10	1.32	1.30
P > F	0.8940	0.5626	0.4056

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.
[1]Number of Russian wheat aphid originally infested/plant on November 8, 1995.

Table 1.29. Mean of total seed weight per meter (g) (± SEM) sampled in 1996 on 3 wheats varying in resistance to Russian wheat aphid, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation levels [1]		
	0 aphids/plant	25 aphids/plant	50 aphids/plant
CO 940626	103.6 ± 28.5a	80.9 ± 20.1a	110.5 ± 22.8a
CO 940252	100.9 ± 25.9a	91.8 ± 26.5a	94.8 ± 9.1a
TAM 107	82.8 ± 23.2a	90.5 ± 22.6a	90.4 ± 39.4a
$Dunn_{0.05}$	11.492	43.866	64.282
F- value	0.68	0.19	1.32
P > F	0.7898	0.7565	0.0659

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.
[1]Number of Russian wheat aphid originally infested/plant on November 8, 1995.

Table 1.30. Mean of one thousand seed weight (g) (± SEM) sampled in 1996 on 3 wheats varying in resistance to Russian wheat aphid, infested at 3 levels. Agricultural Research, Development and Education Center. Fort Collins, CO.

Wheat genotypes	Infestation levels [1]		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	15.2 ± 0.2a	18.8 ± 0.7a	18.2 ± 0.3a
CO 940252	19.5 ± 0.6a	17.8 ± 0.1a	17.2 ± 0.0a
TAM 107	17.7 ± 0.3a	16.7 ± 0.0a	15.6 ± 0.1b
$Dunn_{0.05}$ / $LSD_{0.05}$	4.275	3.2151	1.0323
F- value	1.98	1.81	9.20
P > F	0.8562	0.3089	0.0014

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if P > *F* < 0.05 or $Dunn_{0.05}$ in P > *F* > 0.05.
[1]Number of Russian wheat aphid originally infested/plant on November 8, 1995.

Table 1.31. Mean of grain protein (%) (± SEM) sampled in 1996 on 3 wheats varying in resistance to Russian wheat aphid, infested at 3 levels. Agricultural Research, Development and Education Center. Fort Collins, CO.

Wheat genotypes	Infestation levels [1]		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	12.4 ± 0.3a	12.7 ± 0.4a	12.5 ± 0.2a
CO 940252	12.1 ± 0.1a	12.4 ± 0.3a	12.0 ± 0.1a
TAM 107	13.2 ± 0.4a	13.9 ± 0.0a	12.9 ± 0.0a
$Dunn_{0.05}$	1.0705	1.0814	1.0267
F- value	1.54	1.75	3.12
P > F	0.6542	0.8058	0.2972

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if P > *F* < 0.05 or $Dunn_{0.05}$ in P > *F* > 0.05.
[1]Number of Russian wheat aphid originally infested/plant-tiller on November 8, 1995.

Table 1.32. Mean number of wheat spikes per meter (± SEM) sampled in 1998 on 3 wheats varying in resistance to Russian wheat aphid, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	**Infestation levels [1]**		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	203.3 ± 22.5a	235.0 ± 34.5a	142.3 ± 25.7a
CO 940252	202.3 ± 40.6a	233.1 ± 44.1a	177.1 ± 14.6a
TAM 107	186.6 ± 26.3a	181.3 ± 30.8a	202.6 ± 33.9a
$Dunn_{0.05}$	128.33	166.39	123.43
F- value	0.09	0.55	1.05
P > F	0.9170	0.5921	0.3843

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if P > *F* < 0.05 or $Dunn_{0.05}$ in P > *F* > 0.05.
[1]Number of Russian wheat aphid originally infested/plant on February 27, 1998.

Table 1.33. Mean of total seed weight per meter (g) (± SEM) sampled in 1998 on 3 wheats varying in resistance to Russian wheat aphid, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	**Infestation levels [1]**		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	227.3 ± 41.3a	214.4 ± 23.6a	164.2 ± 31.3a
CO 940252	209.9 ± 31.6a	189.7 ± 24.3a	181.9 ± 6.2a
TAM 107	163.5 ± 37.0a	132.5 ± 25.5a	181.7 ± 42.4a
$Dunn_{0.05}$	4.4981	83.779	113.28
F- value	0.90	2.50	2.88
P > F	0.4385	0.1321	0.0854

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if P > *F* < 0.05 or $Dunn_{0.05}$ in P > *F* > 0.05.
[1]Number of Russian wheat aphid originally infested/plant on February 27, 1998.

Table 1.34. Mean of one thousand seed weight (g) (± SEM) sampled in 1998 on 3 wheats varying in resistance to Russian wheat aphid, infested at 3 levels. Agricultural Research, Development and Education Center. Fort Collins, CO.

Wheat genotypes	Infestation levels [1]		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	38.5 ± 1.0a	35.9 ± 0.3a	37.2 ± 0.6ab
CO 940252	38.5 ± 0.8a	36.5 ± 0.4a	37.4 ± 0.8a
TAM 107	35.5 ± 2.4a	32.6 ± 0.9b	33.4 ± 1.7b
$Dunn_{0.05}/LSD_{0.05}$	5.794	2.2695	3.9175
F- value	1.49	8.45	3.32
P > F	0.2706	0.0071	0.0782

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if P > *F* < 0.05 or $Dunn_{0.05}$ in P > *F* > 0.05.
[1]Number of Russian wheat aphid originally infested/plant on February 27, 1998.

Table 1.35. Mean of grain protein (%) (± SEM) sampled in 1998 on 3 wheats varying in resistance to Russian wheat aphid, infested at 3 levels. Agricultural Research, Development and Education Center. Fort Collins, CO.

Wheat genotypes	Infestation levels [1]		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	12.5 ± 0.4a	12.1 ± 0.3b	12.4 ± 0.2a
CO 940252	11.8 ± 0.2a	12.4 ± 0.4b	12.0 ± 0.3a
TAM 107	12.9 ± 0.6a	13.7 ± 0.4a	13.0 ± 0.6a
$Dunn_{0.05}/LSD_{0.05}$	1.5841	1.2788	1.9246
F- value	2.02	4.54	1.05
P > F	0.1831	0.0396	0.3843

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if P > *F* < 0.05 or $Dunn_{0.05}$ in P > *F* > 0.05.
[1]Number of Russian wheat aphid originally infested/plant on February 27, 1998.

Table 1.36. Mean number of wheat spikes per meter (± SEM) sampled in 1999 on 3 wheats varying in resistance to Russian wheat aphid, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation levels [1]		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	189.3 ± 13.8a	232.6 ± 14.6a	251.6 ± 23.7a
CO 940252	224.8 ± 21.2a	213.6 ± 28.5a	228.3 ± 16.0a
TAM 107	222.0 ± 9.3a	235.8 ± 31.0a	226.5 ± 15.8a
$Dunn_{0.05}$	57.457	116.4	61.948
F- value	1.94	0.17	0.85
P > F	0.1938	0.8422	0.4580

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.

[1]Number of Russian wheat aphid originally infested/plant on March 15, 1999.

Table 1.37. Mean of total seed weight per meter (g) (± SEM) sampled in 1999 on 3 wheats varying in resistance to Russian wheat aphid, infested at 3 levels. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	Infestation levels [1]		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	172.4 ± 15.8a	185.4 ± 16.6a	188.3 ± 14.2a
CO 940252	203.9 ± 20.2a	199.0 ± 28.7a	202.8 ± 12.0a
TAM 107	203.1 ± 9.3a	185.0 ± 19.8a	141.0 ± 11.2b
$Dunn_{0.05}/LSD_{0.05}$	63.454	103.02	43.367
F- value	1.32	0.10	5.50
P > F	0.3091	0.9072	0.0244

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if $P > F < 0.05$ or $Dunn_{0.05}$ in $P > F > 0.05$.

[1]Number of Russian wheat aphid originally infested/plant on March 15, 1999.

Table 1.38. Mean of one thousand seed weight (g) (± SEM) sampled in 1999 on 3 wheats varying in resistance to Russian wheat aphid, infested at 3 levels. Agricultural Research, Development and Education Center. Fort Collins, CO.

Wheat genotypes	Infestation levels [1]		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	32.9 ± 0.9b	33.9 ± 2.2a	31.4 ± 0.5b
CO 940252	35.6 ± 0.4a	33.7 ± 0.4a	34.3 ± 1.0a
TAM 107	35.2 ± 0.5a	32.2 ± 0.3a	30.7 ± 0.5b
$Dunn_{0.05}/LSD_{0.05}$	2.2093	5.3523	2.0336
F- value	4.47	0.52	9.55
P > F	0.0410	0.6089	0.0048

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if P > *F* < 0.05 or $Dunn_{0.05}$ in P > *F* > 0.05.
[1]Number of Russian wheat aphid originally infested/plant on March 15, 1999.

Table 1.39. Mean of grain protein (%) (± SEM) sampled in 1999 on 3 wheats varying in resistance to Russian wheat aphid, infested at 3 levels. Agricultural Research, Development and Education Center. Fort Collins, CO.

Wheat genotypes	Infestation levels [1]		
	0 aphids/plant	**25 aphids/plant**	**50 aphids/plant**
CO 940626	11.8 ± 0.5a	12.0 ± 0.3a	11.8 ± 0.6b
CO 940252	11.0 ± 0.3b	11.0 ± 0.5a	11.1 ± 0.6c
TAM 107	11.1 ± 0.6ab	11.7 ± 0.2a	12.9 ± 0.5a
$Dunn_{0.05}/LSD_{0.05}$	0.6647	1.245	0.5019
F- value	3.45	2.78	31.20
P > F	0.0725	0.1099	0.0001

Means within a column followed by the same letter (s) are statistically similar according to $LSD_{0.05}$ if P > *F* < 0.05 or $Dunn_{0.05}$ in P > *F* > 0.05.
[1]Number of Russian wheat aphid originally infested/plant on March 15, 1999.

Conclusions

Russian wheat aphid population densities varied over the study period. Resistant wheats had low aphid densities compared to the susceptible wheats. Resistant wheats affected Russian wheat aphid development over three years of study. Intense rainfall affected Russian wheat aphid on resistant wheats more than aphids on the susceptible cultivar in 1996. Delays were observed in the expression of wheat genotypic effects on aphid development, probably due to maternal effects. Strong evidence for antibiosis was observed for CO 940626 and CO 940252, based on differences in age structure. Different initial aphid infestation levels resulted in distinct densities throughout the study periods. The high initial infestation level generally had more effect on plant and aphid parameters than the lower levels.

More parasitoid mummies were observed on TAM 107 than on resistant wheats. Leaf structure therefore did not affect parasitoid abundance. Parasitoid density dependence was observed in two years. Predator abundance in sweep samples was too limited to correlate with wheat genotypes or aphid density.

The high Russian wheat aphid infestation level affected the quality of seeds in CO940626 and TAM 107. Increased grain protein was observed in the susceptible wheat and may have been due to aphid stress or lower test weight.

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Chapter 2

Effects of biotic and abiotic factors on Russian wheat aphids infesting wheats differing in categories of resistance

Introduction

Russian wheat aphid, *Diuraphis noxia* (Mordvilko), is a major insect pest of small grains in western United States and Canada. Russian wheat aphid has spread rapidly across the United States since its discovery, causing major economics losses. Direct losses have ranged from $129.3 million in 1988 to $6.4 million in 1991. From 1987 to 1993, estimated direct losses were $432.5 millions (Morrison and Peairs 1998).

Effect of abiotic factors.

Rainfall has adverse effects on aphid populations. *Metopolophium dirhodum* (Walker), *Sitobion avenae* (F.) and *Rhopalosiphum padi* (L.) population densities were evaluated using mesh cloth cages that allowed simulated and natural rain to enter. Simulated rain of 15 mm during 30 minutes produced a 58% of displacement of aphids from plant while a natural rainfall of 7.4 mm displaced 39% (Zuniga 1982). Dhaliwal and Singh (1975) considered rainfall as one of the most important aphid mortality factors. Ten mm of rainfall reduced up to 82% of nymphs of the wheat aphid, *Macrosiphum miscanthi* (Takahashi), and 74% of adults. Al-Mallah and Mohammad (1988) found a negative correlation between a leaf rolling aphid, *Dysaphis pyri* (Boy), population on apple trees and rain in 1986 (r = -0.34) and in 1987 (r = -0.37). Nasir et al. (1998) found that the mustard aphid, *Lipaphis erysimi* (Kalt), densities were negatively correlated with rainfall (r = -0.03) on mustard and rapesseed. Recently, Liang et al. (1998) found that *D. noxia* infestation of spring wheat was negatively correlated with the amount of rainfall in April and May (r = -0.92), but positively correlated to the amount of rainfall in late July (r = 0.67) between 1989 and 1996 in the Xinjiang Uygur Autonomous

Region. China.

Temperature affects reproduction and survival of the Russian wheat aphid and successful overwintering could result in major economic wheat losses. The developmental threshold was estimated as -1.57°C (Girma 1990). According to Aalbersberg et al. (1987), the heat requirements in degree days (DD). from birth to reproduction stage for Russian wheat aphid, was 158.73 DD. The effects of temperature fluctuation were investigated in three temperature regimes 6.4-17.6, 14.4-25.6 and 21.4-32.6°C, by Kieckhefer and Elliott (1989) and the lower threshold for immature development found was 4.1°C. Michels and Behle (1989) found that from 5.0 to 20.0°C Russian wheat aphid nymph production per day increased but decreased from 20.0 to 30.0°C. Super-cooling point of laboratory reared Russian wheat aphid was found to be -24.0°C to -29.0°C depending on instar (Butts 1992). Also, field populations of Russian wheat aphid could survive average daily temperatures ranging from -5.0 to -20.0°C for 20 days on winter wheat in Canada. However, Harvey and Martin (1988) found that Russian wheat aphid survived temperatures as low as -20.8 to -21.5°C but greenbug, *Schizaphis graminum* (Rondani), could not survive such exposure. Snowcover insulated Russian wheat aphid from extreme temperature drops caused by fast-moving cold fronts, allowing temperatures to stabilize at two or three degrees below 0.0°C (Armstrong and Peairs 1996). The insulation provided by rolled leaves may partly explain the relative winter-hardiness of Russian wheat aphid compared to other cereal aphids (Armstrong 1994).

Effects of biotic factors in northern Colorado.

Natural enemies can reduce Russian wheat aphid population densities, although not necessarily sufficiently to prevent economic damage. Over 100 species of natural enemies have been associated with Russian wheat aphid worldwide (Mohamed 1995). Many of these, mostly coccinellids and braconids, have been introduced to over 20 countries in Asia, Europe, Africa and South America. Coccinellids are often abundant in Russian wheat aphid infested wheat, but may not be effective predators due to their limited ability to search within rolled leaves (Kauffman and La Roche 1994).

The mechanical exclusion or cage exclusion technique was first used to evaluate the efficacy of introduced parasitoids on black scale *Saissetia oleae* (Bern) (Smith and DeBach 1942). Knutson and Gilstrap (1989) used exclusion cages to evaluate the effects of natural enemies on larvae and eggs of southwestern corn borer, *Diatraea grandiosella* (Dyar). Cages were also used for European corn borer, *Ostrinia nubilalis* (Hübner), (Sparks et al. 1966), soybean looper, *Pseudoplusia includens* (Walker), (Richman et al. 1980), and the leaf mining lepidopteran, *Carmaria* sp. (Faeth and Simberloff 1981).

Differences in microclimate, particularly temperature, had been cited as a limiting factor for this method (Smith and DeBach 1942). However, they used different construction materials from those used to study Russian wheat aphid (Hopper et al. 1995; Mohamed 1995; Nechols and Harvey 1998). Nechols and Harvey (1998) reported no temperature effects caused by cages. Mohamed (1995) observed no visual differences in plant quality between caged and uncaged plants.

Russian wheat aphid population densities increased 2 to 19 fold on caged plants compared to aphids on uncaged plants in southern France (Hopper et al. 1994). Mohamed (1995) found that Russian wheat aphid densities increased between 3 to 11 fold on caged plants compared to uncaged plants, in northern Colorado. Nevertheless. exclusion cages have limitations including changes in microclimate and interference with pest and natural enemy movement. Additionally, maintaining the cages in the ground is often difficult.

Bayoun et al. (1995) indicated that malathion was effective in the laboratory against predators and parasitoids but had minimum effect on Russian wheat aphid. However, Rao (1996) noted a lack of malathion efficacy against parasitoids and predators when applied in the field.

Both resistant genotypes and biological control can be used for controlling Russian wheat aphids. The combined use of biological control and plant resistant may increase aphid mortality rate. if the resistance category is antibiosis. This may decrease the body size of the prey and in turn increase the functional response of a predator because the predator will satiate more slowly (Farid et al. 1998). Messina et al. (1997) proposed that leaf architecture influenced the effectiveness of two selected predators. Larvae of the lacewing, *Chrysoperla plorabunda* (Fitch). and adults of the lady beetle. *Propylea quatuordecimpunctata* L., were more effective predators on Indian ricegrass. *Oryzopsis hymenoides* (Roemer & Schuites). with flat leaves. than on crested wheatgrass. *Agropyron desertorum* (Fischer ex Link). with rolled leaves. The parasitism rate of *Diaeretiella rapae* (McIntosh) also was greater on aphids infesting resistant unrolled

Triticum spp. leaves versus aphids on susceptible rolled leaves (Reed et al. 1991). Thus, both predators and parasitoids of Russian wheat aphid can be influenced by leaf structure. However, Reed et al. (1992) reported that antibiosis can reduce the parasitoid vitality because of reduced host size. Brewer et al. (1998) reported that uncurled barley leaves did not necessarily provide a better environment for *Aphelinus albipodus* (Hayat and Fatima) and *D. rapae* to parasitize *D. noxia*. Smaller parasitoid size did not seem to be an indicator of success in a physically restricted environment (rolled leaf).

This study was designed to use the exclusion cage method to measure differential biotic and abiotic effects on Russian wheat aphid infesting wheat genotypes differing in category of resistance. It included an intensive measurement of temperature, snowfall, and rainfall during two consecutive winter wheat seasons, 1997-1998 and 1998-1999.

Objective.

The specific objective of this study was to determine the effects of abiotic natural controls (snow, rainfall and temperature) and biotic factors on the interaction of Russian wheat aphid and wheat lines differing in categories of resistance.

Materials and Methods

Plant materials.

Three wheat lines were used in this experiment: (1) CO 940626 containing the Dn4 resistance gene with pedigree CO 850034/T-57//5* TAM 107, (2) CO 940252 containing the Dn6 resistance gene with pedigree TAM 107//PI243781/CO850260, and (3) the susceptible wheat TAM 107 (J. S. Quick, Department of Soil and Crop Sciences. Colorado State University, personal communication).

Field layout and crop management.

Field operations are summarized in Table 2.1. Border rows and buffers were planted to TAM 107 with a tractor-mounted plot planter. However. each 76 cm wide x 9144 cm long plot was hand-planted with a wheel planter except the 1998-1999 season. when a tractor mounted precision plot planter was used.

Table 2.1. Summary of field activities during the study period. Agricultural Research. Development and Education Center. Fort Collins, CO.

Activity	1997-1998	1998-1999
Pre irrigation	August 18. 1997	**September 24. 1998
Planting	September 11, 1997	September 10. 1998
Infestation	November 5, 1997	October 7, 1998
Cages placed	November 15, 1997	October 10, 1998
Temperature loggers	December 1, 1997	November 1, 1998
Monthly sampling started	December 12, 1997	November 18, 1998
Weekly sampling started	May 5, 1998	April 13, 1999
Insecticide	May 21, 1998 June 7,1998 June 15, 1998	March 15. 1999 April 11. 1999 May 1, 1999 May 20, 1999 June 2, 1999
Rain gauges placed	April 20. 1998	March 28. 1999

** First irrigation in 1998-1999 2wks after planting.

Experimental design.

A split plot design was used with six replicates (Steel and Torrie 1980). Each main plot (CO 940626, CO 940252 and TAM 107) was 76 cm wide x 9144 cm long and subdivided into four subplots for each cage treatment.

Cage treatments.

Four exclusion cage treatments were designed as follows:

1= Complete exclusion, closed at sides and top to exclude rain, snow and natural enemies. The cages were 76.2 cm wide, 152.4 cm long and 135.89 cm height. The frames were constructed using iron 1.27 cm diameter reinforcement bars bent to fit cage dimensions. Cage walls and roof were covered with organdy nylon cloth (mesh size 0.4 x 0.5mm, thread thickness 0.1mm) (Hancock Fabrics, Denver, CO) that allowed light for plant growth while excluding natural enemies.

2= Partial exclusion plus insecticide. was similar to the completely closed cage except that it was open at the top to allow rain and snow. Also, cages sides were treated with malathion to control natural enemies. Approximately 1 liter of malathion 50 (The Solaris Group, Monsanto Company, San Ramon, CA) with 426 µl (AI)/l per cage was applied to the interior walls.

A laboratory experiment was conducted to determine the effect of different malathion rates on Russian wheat aphid population to minimize risk of contamination of adjacent cages. Three groups of susceptible wheats infested with Russian wheat aphid were pre-counted and sprayed with the following concentrations (426 µl (AI)/l, 852 µl (AI)/l, 1278 µl (AI)/l). Twenty four hours later Russian wheat aphid number were counted and mortality percent was determined (Table 2.2). The results showed that 426 μl (AI)/l had the lowest mortality rate from direct exposure. However, only the walls of cages used in the partial exclusion with insecticide treatment were to be treated so aphids would not be exposed directly to malathion. Therefore, the 426 μl (AI)/l rate was selected to be used for this exclusion treatment.

Table 2.2. Effect of different rates of malathion 50 on mean (±SEM) of Russian wheat aphid survival after 24 h of treatment.

Treatment	**Russian wheat aphid before treatment**	**Russian wheat aphid post treatment**	**% mortality**
Untreated	17.7±10.2	17.7±10.2	0.00
426 μl (AI)/l	63.5±32.0	26.5±13.0	58
852 μl (AI)/l	125.0±9.0	4.2±0.0	96
1278 μl (AI)/l	212.7±0.0	2.0±0.0	99

3= Partial exclusion, the same as number 2 without malathion treatment.

4= No exclusion, consisted of just the cage frame, without walls or sides.

Plants were infested at approximately growth stage 30 (Zadoks et al. 1974) with 10 Russian wheat aphid mixed with dry Cream of Wheat (R) cereal (Nabisco, Inc. East Hanover, N.J.) per plant and applied to the plant with a Davis inoculator in a manner similar to that described by Calhoun et al. (1990).

Temperature was measured using HOBO (R) data loggers (Onset Computer Corporation, Pocasset, MA). One temperature logger was placed approximately 10cm above soil, in each of the 12 wheat genotype exclusion combinations, at random among replicates, to determine the effect of cage type on temperature accumulations.

Temperature loggers were programmed to record temperature every 72 minutes (Table 2.1). Rainfall was measured with twelve rain gauges placed in the same cages as temperature loggers (Table 2.1). Rain gauges were designed as follows (D. Smith. Department of Soil and Crop Sciences. Colorado State University, personal communication 1996):

- Two small funnels made of plastic, held by plastic frame.
- A plastic hose connecting the funnels to a graduated cylinder to accumulate and measure rainfall.
- The graduated cylinder was filled one quarter with antifreeze (ethylene glycol) to avoid evaporation.
- Metal bar with clips to hold the gauges.

Sampling and data collection.

All cage treatments were sampled at the same time (Table 2.1). The first sample were taken at approximately three weeks after infestation. Six tillers per plot were removed once a month starting in late fall and once a week starting in late spring until crop maturity. Samples were placed in Ziploc^R bags (S. C. Johnson & Son. Inc., Racine. WI) labeled with the date and subplot number. The bags were put in a cooler during transport to the laboratory. Samples were examined for parasitoid mummies and then placed individually in Berlese funnels for 24 hours (Armstrong et al. 1991). Russian wheat aphids were extracted into jars containing 80% ethanol. and labeled with the corresponding subplot number. for subsequent sorting and counting. During each sampling date coccinellids predators (adults and larvae) were counted for 1 minute per subplot; all predator counts were made by the same person.

Snow was measured in cm by metal ruler at three randomly selected points in the temperature logger subplots and snow duration also was recorded after each snow event. Rainfall in millimeter was recorded after each event. Temperature logger data were downloaded every three months.

Statistical analysis.

Table 2.3 shows the analysis of variance of split-plot experiment. The general linear model used was:

$$Y_{ijk} = M + P_i + {}_j + E_i + y_{ij} + B_k + (\ B)_{ik} + E_{ijk}$$ (Steel and Torrie 1980).

i = TAM107, CO 940626 and CO 940252.,

J = Block effect.,

K = Cage treatment (1,2,3 and 4). Only 3 cages for weather data.

Table 2.3. Analysis of variance for split-plot design with wheat as main plot and cages as a subplots.

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	F
Total	71			
Replications	5	SS Replicate	MSR	
Main-plot				
(Wheat)	2	SS Wheat	MSW	F_{Wheat}
Error	10	SSError	MSE	
Sub-plot				
(Cages)	3	SSCages	MSC	F_{cages}
Cagesx Wheat	6	SS (Cages* Wheat)	MS(Cages* Wheat)	$F_{cages*Wheat}$
Error	45	SSError		

Data analysis.

Russian wheat aphid counts were analyzed using Proc Mixed and LSMeans (SAS 1996). This program is limited in detection of sub-plot interactions. Therefore, in order to construct a general statement for the analysis, three months were selected to represent each season and analyzed separately to get an overview statement. The rest of data analysis was on a monthly basis. F-value and p-values are reported in the tables. Aphid counts were transformed by the square root method if the need to do so was indicated by the shape of residual plots (SAS 1996). During the 1998 - 1999 season greenbug, *Schizaphis graminum* (Rondani), was analyzed as one of the variables affecting Russian wheat aphid density. Therefore, competition effects were determined based on that.

Temperature data were summarized using SAS and maximum, minimum and average temperature were calculated. Accumulated degree hours below 0.0°C (ADH0) were determined for each sampling date, cage treatment with different wheat genotype, and each year. Sub zero accumulations were calculated by summing the average temperature of each h below 0.0°C. (For example, if on a given day the average hourly temperature were -2.0°C at h 0800, -6.0°C at h 0900, and -10.0°C at h 1000 the ADH0 for the day will be -18.0°C). Then the number of hours with negative temperatures were summed for each hourly average temperature below 0.0°C (AH0) for every sampling date (Armstrong and Peairs 1996). However, 20°C was chosen as the upper favorable temperature limit (Michels and Behle 1988). Accumulated degree hours above 20°C (ADH20) were calculated similarly.

The snowfall amount received for exclusion treatment were calculated for all cage exclusion treatments. Both partial exclusion treatments were combined togther because of the similarity in snowfall received, creating an unbalanced analysis. PROC GLM was applied to test the effects of exclusion on snowfall amounts received. The same procedure was followed for rainfall effects. Then average daily snowcover (ADSC) and average daily rain fall (ADRF) were calculated from snow and rain observations.

Natural enemy (NE) (parasitoids and predators) counts were analyzed separately. Parasitoid counts were analyzed after sorting by wheat genotype. All the above parameters were analyzed by PROC GLM each year for each wheat genotype / exclusion cage type combination. Means were compared by Fisher's LSD method if P>F was <0.05 and by Bonferroni's method if P>F >0.05 (Milliken and Johnson 1984).

All parameters (ADH0, AH0, ADSC, ADH20, AH20, ADRF and NE) were then used as independent variables in regression models, with Russian wheat aphid density per tiller as the dependent variable. Two different data sets were created. The first contained winter data from December 1997-March 1998 and November 1998- March 1999. The independent variables were (ADH0, AH0, ADSC) with Russian wheat aphid per tiller as dependent variable. This was done for each exclusion treatment / wheat genotype combination. The other data set included spring data collected during April 1998 - June 1998 and April 1999 - June 1999 with ADH20, AH20, ADRF and NE used as independent variables and Russian wheat aphid per tiller as the dependent variable.

Multiple regression models were calculated using the PC SAS PROC REG procedure, followed by selection = MAXR, CP and MSE statements. The MAXR statement allows for all combinations of regression to be included or deleted in a step-wise order.

Results and Discussions

Population density.

Russian wheat aphid densities varied among different wheat genotypes during the season from December 1997 until July 1998 ($F = 34.10$, df = 2, $P < 0.0001$) and from November 1998 until June 1999 ($F = 25.99$, df = 2, $P < 0.0001$) based on the representative month PROC-MIXED analyses (Figs 2.1,2.2). Similar results were observed in 1996, 1998 and 1999 in the study reported in Chapter 1. Russian wheat aphid density on the susceptible wheat TAM 107 was three times higher than on either resistant wheat in both seasons. Densities were similar on CO 940626 and CO 940252 wheat genotype affected aphid development indicating antibiotic resistance.

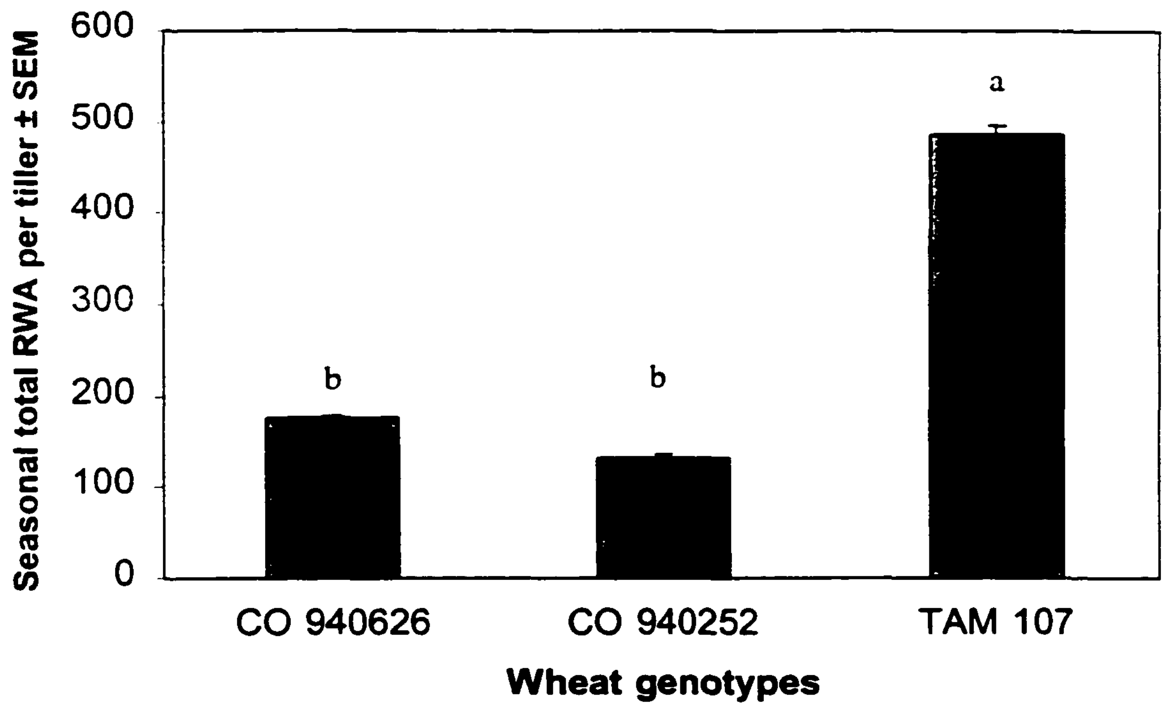

Fig 2.1. Mean (± SEM) Russian wheat aphids (RWA) per tiller collected from 3 wheats differing in aphid resistance, averaged over 4 exclusion cage types, December 1997- July 1998, Agricultural Research, Development and Education Center, Fort Collins, CO. Bars marked with different letters are significantly different, Fisher protected LSD (α=0.05).

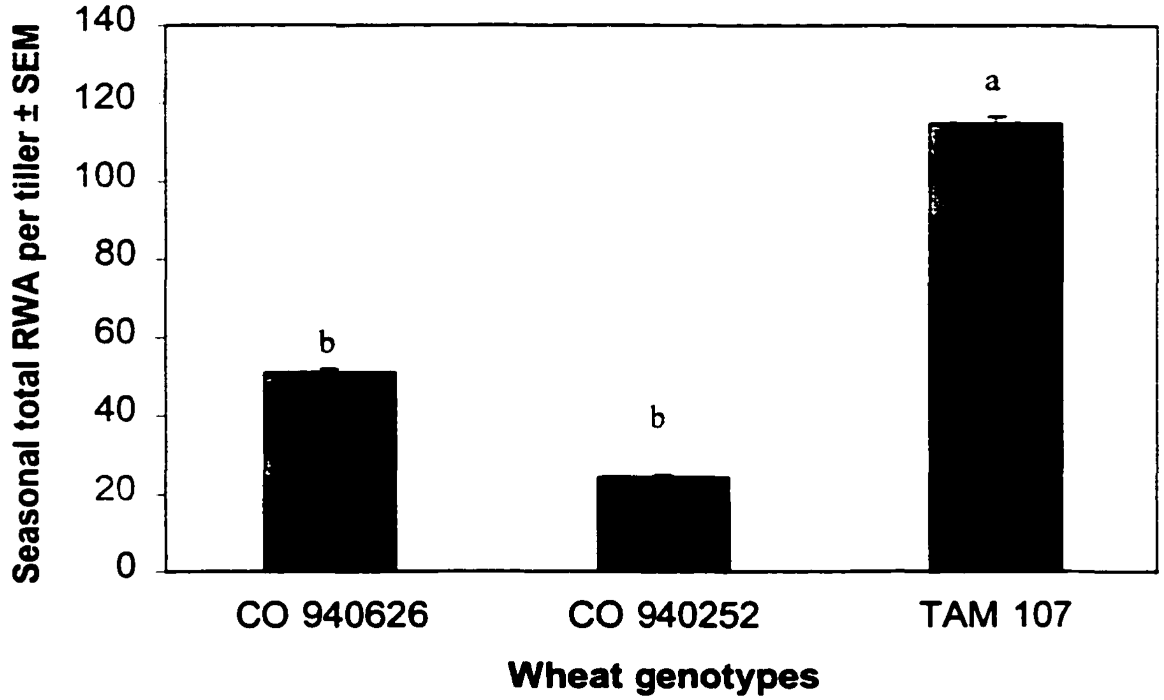

Fig 2.2. Mean (± SEM) Russian wheat aphids (RWA) per tiller collected from 3 wheats differing in aphid resistance, averaged over 4 exclusion cage types, November 1998-June 1999. Agricultural Research, Development and Education Center, Fort Collins, CO. Bars marked with different letters are significantly different, Fisher protected LSD (α=0.05).

Aphid population densities varied under the four cage treatments in 1997-1998 ($F = 3.48$, df = 3, P = 0.0226) and in 1998-1999 ($F = 6.85$, df = 3, P = 0.0008) for the representative month analysis (Figs 2.3, 2.4). In the first season, the complete exclusion treatment had more Russian wheat aphids than the other exclusion treatments, as expected, since Russian wheat aphids were protected from detrimental biotic and abiotic factors. However, in 1998-1999 Russian wheat aphid abundance in the no exclusion treatment was similar to the complete exclusion treatment (Fig 2.4). This difference might due to the lack of environmental detrimental influence during 1998-1999 season. Differences were observed among cage treatments in both seasons (Tables 2.4, 2.5). Exclusion effects were less than those observed by Hopper et al. (1995) and Mohamed (1995), although years were not similar more aphid were found in partial exclusion plus insecticide than in partial exclusion. Caution should taken interpreting these results because they are derived from the three representative months in each year.

Among selected three months in 1997-1998 season (F= 87.63, df=2, P < 0.0001) and 1998-1999 (F= 73.09, df=2, P < 0.0001). Densities remained low until spring. Genotypic differences were not observed until April or May, when more aphids were observed on TAM 107. Low population densities during winter and early spring in Colorado is normal for Russian wheat aphid (Peairs 1990), as is the rapid population increase observed at the end of spring and early summer in both seasons. In 1998 aphid densities declined first on TAM 107, due to the earlier maturity of that wheat (Fig 2.5). However, sampling in the second year was terminated based on the declining population densities in the study reported in Chapter 1 before noticeable declines occurred in this study (Fig 2.6). Russian wheat aphid population densities were lower in 1998-1999 than in 1997-1998. Greenbug abundance during November 1998 Russian wheat aphids (F = 3.46, df = 4, P = 0.0131), similarly in May 1999 (F = 9.55, df = 70, P < 0.0001).

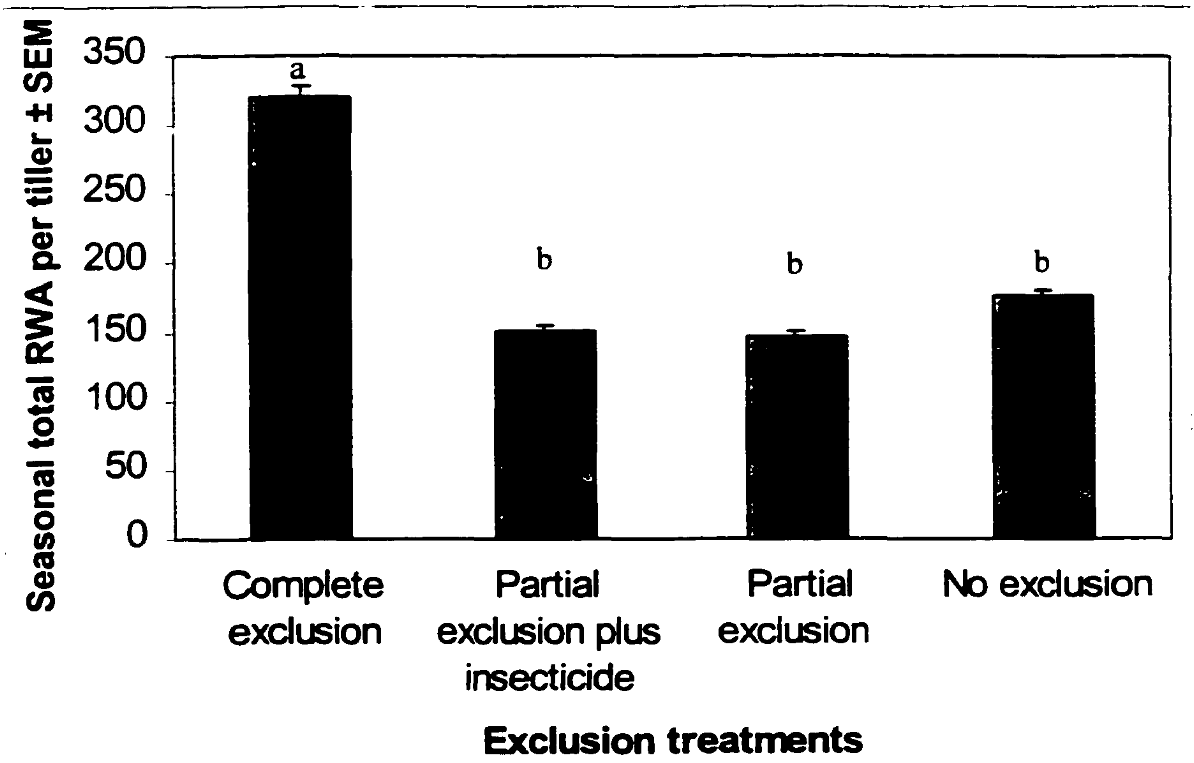

Fig 2.3. Mean (± SEM) Russian wheat aphids (RWA) per tiller collected from 4 exclusion cage treatments averaged over three wheats differing in aphid resistance. December 1997-July 1998. Agricultural Research. Development and Education Center. Fort Collins. CO. Bars marked with different letters are significantly different. Fisher protected LSD (α=0.05).

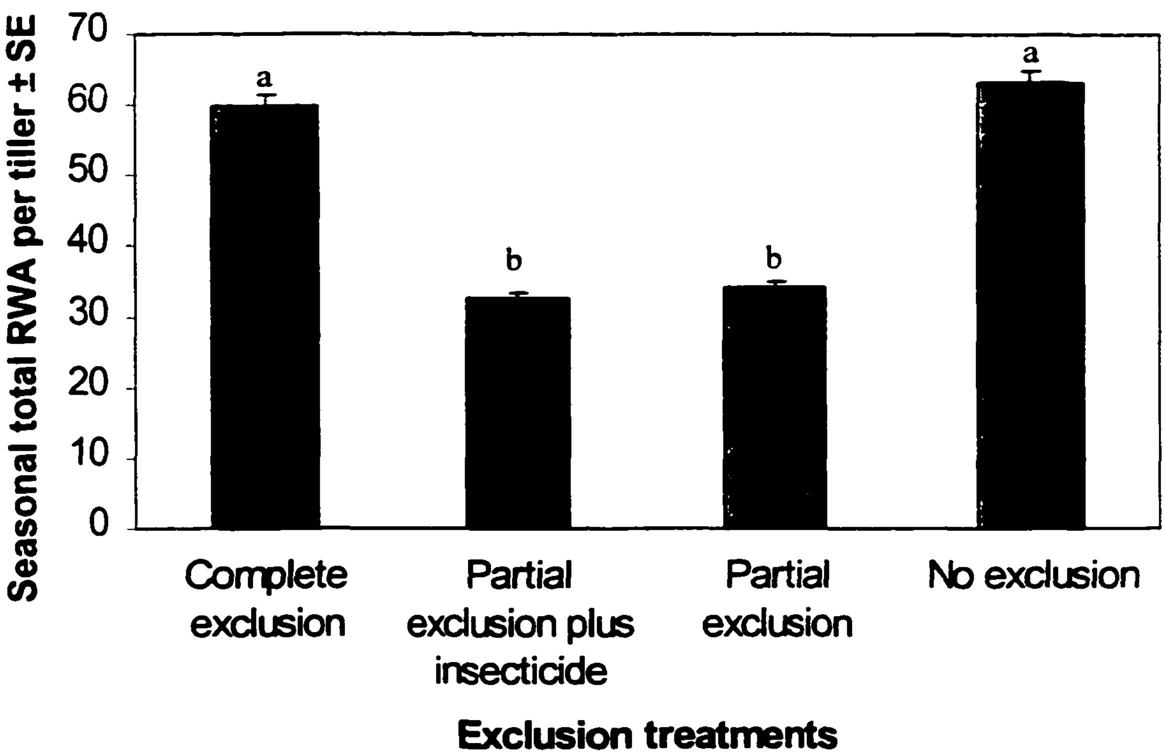

Fig 2.4. Mean (± SEM) Russian wheat aphids (RWA) per tiller collected from 4 exclusion cage treatments averaged over three wheats differing in aphid resistance. November 1998-June 1999. Agricultural Research, Development and Education Center. Fort Collins. CO. Bars marked with different letters are significantly different. Fisher LSD (α=0.05).

Table 2.4. Mean number of Russian wheat aphid per tiller (± SEM) sampled for 3 months representing December 1997 - July 1998 on 3 wheats differing in aphid resistance, from 4 exclusion cage treatments. Agricultural Research, Development and Education Center, Fort Collins, CO.

Exclusion treatment	**Aphids per tiller**
Complete exclusion	1.0 ± 0.0a
Partial exclusion plus insecticide	0.7 ± 0.0b
Partial exclusion	0.6 ± 0.0c
No exclusion	0.4 ± 0.0d
F-value	3.48
P>F	0.0001

Means within columns followed by the same letter are not significantly different (α=0.05, LSMeans)(SAS 1996).

Table 2.5. Mean number of Russian wheat aphid per tiller (± SEM) sampled for 3 months representing November 1998- June 1999 on 3 wheats differing in aphid resistance, from 4 exclusion cage treatments. Agricultural Research, Development and Education Center, Fort Collins, CO.

Exclusion treatment	**Aphids per tiller**
Complete exclusion	1.0 ± 0.2c
Partial exclusion plus insecticide	1.0 ± 0.2b
Partial exclusion	0.8 ± 0.2d
No exclusion	2.4 ± 0.2a
F-value	6.85
P>F	0.0008

Means within columns followed by the same letter are not significantly different (α=0.05, LSMeans)(SAS 1996).

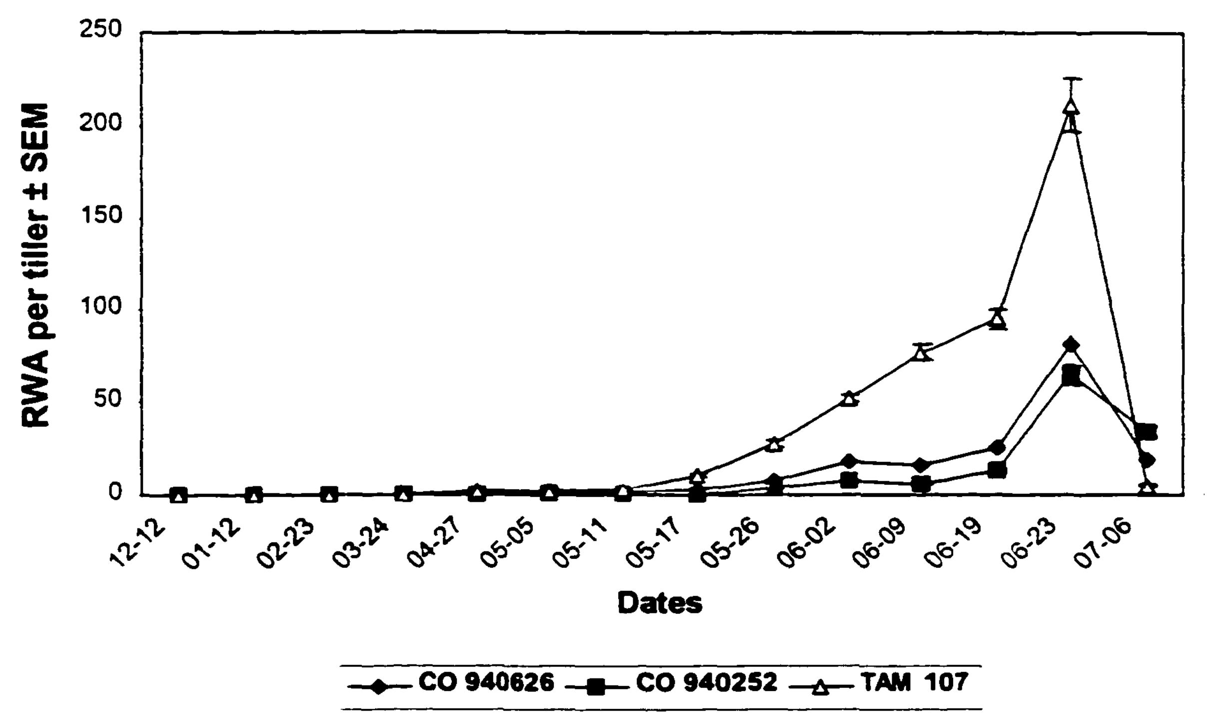

Fig 2.5. Mean (± SEM) Russian wheat aphids (RWA) per tiller collected from resistant and susceptible wheats, summarized over 4 exclusion cage treatments, December 1997-July 1998. Agricultural Research Development and Education Center, Fort Collins, CO.

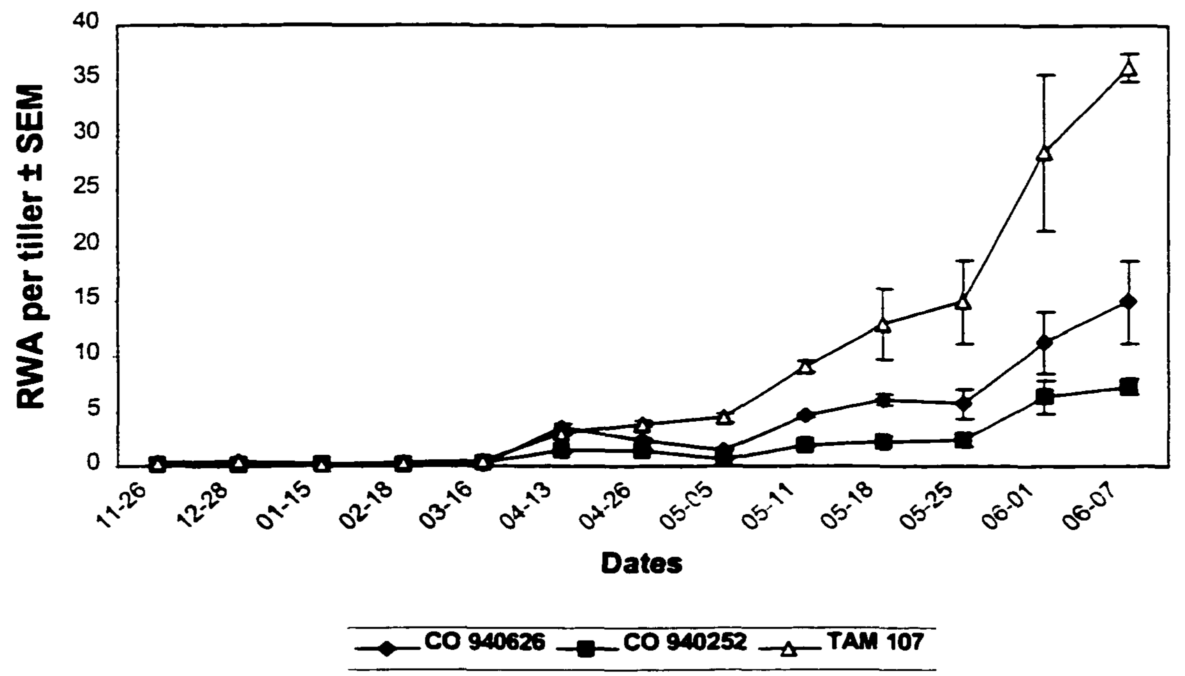

Fig 2.6. Mean (± SEM) Russian wheat aphids (RWA) per tiller collected from resistant and susceptible wheats, summarized over 4 exclusion cage treatments, November 1998-June 1999. Agricultural Research, Development and Education Center. Fort Collins, CO.

Exclusions, wheat genotypes and Russian wheat aphids.

Both CO 940626 and CO 940252 had similar effects on aphid abundance. compared with TAM 107 (Tables 2.6 and 2.7). TAM 107 had the greatest aphid abundance (Tables 2.6 and 2.7). Exclusion treatments differed in their effect on aphid densities with different wheats. The complete exclusion cage treatment always had greater aphid abundance because of the protection against detrimental environmental factors provided by this treatment compared to the two partial exclusion treatments. TAM 107 with exclusions always had greater aphid abundance compare to the two resistant wheat with exclusion treatments (Tables 2.6 and 2.7). Two reasons for this observation, exclusion treatment protection and secondly leaf curling protection from biotic and abiotic factors. Russian wheat aphid densities on resistant wheats were not affected by the use of insecticides (Tables 2.6 and 2.7). Natural enemies might not have been exposed to the insecticide because of protection provided by the aphid mummies Rao (1996) and might be due to inactivity of malathion in the field against natural enemies as was observed by Rao (1996).

Table 2.6. Mean number of Russian wheat aphid per tiller (± SEM) sampled for 3 months representing December 1997- July 1998 on 3 wheats differing in aphid resistance, grown in different exclusion cages. Agricultural Research, Development and Education Center, Fort Collins, CO.

	Wheat genotype	**Aphids per tiller**			
		Complete exclusion	**Partial exclusion plus insecticide**	**Partial exclusion**	**No exclusion**
	CO 940626	0.9 ± 0.1bA	0.4 ± 0.1bB	0.6 ± 0.1abB	0.6 ± 0.1bB
	CO 940252	0.6 ± 0.1cA	0.4 ± 0.1bA	0.4 ± 0.1bA	0.4 ± 0.1bA
	TAM 107	1.4 ± 0.1aA	1.1 ± 0.1aA	0.8 ± 0.1aB	1.0 ± 0.1aA
F- value	3.48	34.10			
P > *F*	0.0226	0.0001			

Means within rows and columns followed by the same letter (upper case, rows and lower case, columns) are not significantly different (α=0.05, LSMeans)(SAS 1996).

Table 2.7. Mean number of Russian wheat aphid per tiller (± SEM) sampled for 3 months representing November 1998- Jun 1999 on 3 wheats differing in aphid resistance, grown in different exclusion cages. Agricultural Research, Development and Education Center. Fort Collins. CO.

	Wheat genotype	**Aphids per tiller**			
		Complete exclusion	**Partial exclusion plus insecticide**	**Partial exclusion**	**No exclusion**
	CO 940626	0.9 ± 0.4bA	0.7 ± 0.4bB	1.0 ± 0.4aAB	1.6 ± 0.4bA
	CO 940252	0.7 ± 0.4bA	0.2 ± 0.4cB	0.4 ± 0.4bAB	0.6±0.4cAB
	TAM 107	1.3 ± 0.4aB	2.2 ± 0.4aBA	1.3 ± 0.4aB	5.3 ± 0.4aA
F-value	6.85	25.99			
P > *F*	0.0008	0.0001			

Means within rows and columns followed by the same letter (upper case, rows and lower case, columns) are not significantly different (α=0.05, LSMeans)(SAS 1996).

The interaction between Russian wheat aphid. wheat genotypes and exclusion treatment by month was significant in 1997-1998 (F= 88.9, df=12, P = 0.0159) and 1998-1999 (F= 5.32, df=12, P < 0.0001) in the representative month analysis. The complete exclusion had greater densities in both years (Tables 2.8 and 2.9). Different wheat genotypic effects were observed over months in 1997-1998 (F= 29.29, df=4, P < 0.0001) and 1998-1999 (F= 17.30, df=4, P < 0.0001) for the representative months. During December 1997, January 1998-April 1998, the effects of wheat genotype and exclusion treatment were not clearly observed due to the low aphid abundance normally observed during winter (Peairs 1990) (Tables 2.8, 2.9). As abundance increased in late March 1998 and May 1999, the interaction started to appear and wheat genotype and exclusion treatment effects became more clear (Tables 2.8, 2.9). As wheats start to mature and dry down and Russian wheat aphid abundance decreased interaction effects again became less apparent (Tables 2.8. 2.9). Therefore. sufficient Russian wheat aphid density is required to observe effects of wheat genotype and exclusion treatment (Tables 2.8 and 2.9). Natural enemies usually become active in late May and early June as aphid pray become readily available (Mohammed 1994). Insecticide use did not affect aphid densities in the partial exclusion treatments (Table 2.8 and 2.9). even though malathion applications were increased from three in the first year to five in the second year. Parasitoids and predators might not have come into contact with treated cage walls. or they might be more tolerant to malathion than was first reported (Rao 1996). One additional reason of the lack of natural enemies effects might be due to the exclusion design. a cage open at the sides might interact differently with natural enemies than a cage open at the top.

Table 2.8. Effect of plant resistance and exclusion cage type on Russian wheat aphid densities per tiller (± SEM) per sampling date, monthly from December 1997 until July 1998. Agricultural Research, Development and Education Center, Fort Collins, CO.

	Wheat genotypes	Aphid per tiller			
		December 1997			
		Complete exclusion	Partial exclusion plus insecticide	Partial exclusion	No exclusion
	CO 940626	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	CO 940252	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	TAM 107	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
F-value	0.38	0.37			
P > *F*	0.7674	0.6968			
		January 1998			
	CO 940626	0.1 ± 0.0abA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	CO 940252	0.0 ± 0.0bA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	TAM 107	0.1 ± 0.0aA	0.0 ± 0.0aBC	0.0 ± 0.0aAC	0.0 ± 0.0aAC
F-value	1.64	0.61			
P > *F*	0.1925	0.5548			

	Wheat genotypes	Aphid per tiller			
		February 1998			
		Complete exclusion	Partial exclusion plus insecticide	Partial exclusion	No exclusion
	CO 940626	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	CO 940252	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	TAM 107	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
F-value	0.62	0.56			
P > *F*	0.6039	0.5854			
		March 1998			
	CO 940626	0.0 ± 0.0bA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	CO 940252	0.1 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	TAM 107	0.1 ± 0.0aA	0.0 ± 0.0aB	0.0 ± 0.0aB	0.0 ± 0.0aB
F-value	2.64	3.04			
P > *F*	0.0574	0.0552			

	Wheat genotypes	Aphid per tiller			
		April 1998			
		Complete exclusion	**Partial exclusion plus insecticide**	**Partial exclusion**	**No exclusion**
	CO 940626	0.2 ± 0.0bA	0.0 ± 0.0aA	0.1 ± 0.0aA	0.1 ± 0.0aA
	CO 940252	0.1 ± 0.0bA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	TAM 107	1.3 ± 0.0aA	0.2 ± 0.0aB	0.1 ± 0.0aC	0.0 ± 0.0ad
F-value	3.63	3.65			
P > *F*	0.0178	0.0319			
		May 1998			
	CO 940626	2.1 ± 0.6bA	0.3 ± 0.6bB	0.6 ± 0.6aBA	0.2 ± 0.6aB
	CO 940252	1.1 ± 0.6bA	0.0 ± 0.6bA	0.0 ± 0.6aA	0.0 ± 0.6aA
	TAM 107	6.3 ± 0.6aA	2.2 ± 0.6aB	0.9 ± 0.6aB	1.1 ± 0.6aB
F-value	11.75	12.06			
P > *F*	0.0001	0.0008			

	Wheat genotypes	Aphid per tiller			
		June 1998			
		Complete exclusion	Partial exclusion plus insecticide	Partial exclusion	No exclusion
	CO 940626	13.7 ± 6.0bA	6.0 ± 6.0bA	7.0 ± 6.0abA	8.5 ± 6.0abA
	CO 940252	10.4 ± 6.0bA	2.8 ± 6.0bA	3.6 ± 6.0bA	5.9 ± 6.0bA
	TAM 107	43.8 ± 6.0aA	22.3 ± 6.0aB	20.1 ± 6.0aB	22.5 ± 6.0aB
F-value	3.99	7.92			
P > *F*	0.0084	0.0045			
		July 1998			
	CO 940626	2.8 ± 4.4aA	4.3 ± 4.4aA	7.9 ± 4.4aA	3.6 ± 4.4bA
	CO 940252	3.3 ± 4.4aB	8.2 ± 4.4aBC	7.7 ± 4.4aB	14.7 ± 4.4aAC
	TAM 107	0.5 ± 4.4aA	1.4 ± 4.4aA	0.1 ± 4.4aA	2.7 ± 4.4bA
F-value	0.85	1.35			
P > *F*	0.4734	0.2900			

Means within rows and columns followed by the same letter (upper case, rows and lower case, colums) are not significantly different (α=0.05, LSMeans)(SAS 1996).

Table 2.9. Effect of plant resistance and exclusion cage type on Russian wheat aphids densities per tiller (± SEM) per sampling date, monthly from November 1998 until June 1999. Agricultural Research, Development and Education Center, Fort Collins, CO.

	Wheat genotypes	**Aphid per tiller**			
		November 1998			
		Complete exclusion	**Partial exclusion plus insecticide**	**Partial exclusion**	**No exclusion**
	CO 940626	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	CO 940252	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	TAM 107	0.0 ± 0.0aB	0.1 ± 0.0aBA	0.0 ± 0.0aB	0.1 ± 0.0aA
F-value	1.02	1.74			
P > *F*	0.3920	0.2086			
		December 1998			
	CO 940626	0.0 ± 0.0aA	0.1 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	CO 940252	0.0 ± 0.0aA	0.0 ± 0.0bA	0.0 ± 0.0aA	0.0 ± 0.0aA
	TAM 107	0.1 ± 0.0aA	0.1 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
F-value	0.82	0.94			
P > *F*	0.4917	0.4121			

	Wheat genotypes	Aphid per tiller			
		January 1999			
		Complete exclusion	Partial exclusion plus insecticide	Partial exclusion	No exclusion
	CO 940626	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	CO 940252	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	TAM 107	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
F-value	0.29	0.14			
P > *F*	0.8344	0.8729			
		February 1999			
	CO 940626	0.0 ± 0.0bA	0.0 ± 0.0bAC	0.0 ± 0.0aBC	0.0 ± 0.0aAC
	CO 940252	0.0 ± 0.0cA	0.0 ± 0.0bA	0.0 ± 0.0aA	0.0 ± 0.0aA
	TAM 107	0.1 ± 0.0aA	0.1 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
F-value	0.30	4.63			
P > *F*	0.8284	0.0271			

	Wheat genotypes	Aphid per tiller			
		March 1999			
		Complete exclusion	Partial exclusion plus insecticide	Partial exclusion	No exclusion
	CO 940626	0.0 ± 0.0cA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	CO 940252	0.1 ± 0.0bA	0.0 ± 0.0aA	0.0 ± 0.0aA	0.0 ± 0.0aA
	TAM 107	0.2(0.0)aA	0.0 ± 0.0aB	0.1 ± 0.0aB	0.0 ± 0.0aB
F-value	1.21	2.36			
P > *F*	0.3129	0.1030			
		April 1999			
	CO 940626	0.8 ± 0.3aAB	0.4 ± 0.3aB	0.2 ± 0.3aB	1.3 ± 0.3aA
	CO 940252	0.3 ± 0.3aA	0.5 ± 0.3aA	0.1 ± 0.3aA	0.3 ± 0.3bA
	TAM 107	1.3 ± 0.3aA	0.5 ± 0.3aBC	0.4 ± 0.3aC	1.1 ± 0.3aAB
F-value	3.27	1.35			
P > *F*	0.0239	0.2881			

	Wheat genotypes	**Aphid per tiller**			
		May 1999			
		Complete exclusion	**Partial exclusion plus insecticide**	**Partial exclusion**	**No exclusion**
	CO 940626	0.8 ± 0.3bA	0.5 ± 0.3aA	0.8 ± 0.3aA	0.7 ± 0.3bA
	CO 940252	0.5 ± 0.3bA	0.1 ± 0.3aA	0.3 ± 0.3aA	0.2 ± 0.3bA
	TAM 107	3.0 ± 0.3aA	0.8 ± 0.3aB	0.7 ± 0.3aB	2.0 ± 0.3aA
F-value	5.33	7.48			
P > *F*	0.0014	0.0056			
		June 1999			
	CO 940626	2.8 ± 1.1aA	1.9 ± 1.1bA	3.2 ± 1.1abA	3.1 ± 1.1bA
	CO 940252	2.9 ± 1.1aA	0.2 ± 1.1bBC	1.1 ± 1.1bBA	2.0 ± 1.1bA
	TAM 107	3.5 ± 1.1aB	6.1 ± 1.1aB	4.8 ± 1.1aB	13.8 ± 1.1aA
F-value	4.57	33.62			
P > *F*	0.0045	0.0001			

Means within rows and columns followed by the same letter (upper case rows and lower case, colums) are not significantly different (α=0.05, LSMeans)(SAS 1996).

Biotic and abiotic measurements.

Both abiotic and biotic factors affect Russian wheat aphid population dynamics. Temperature differed over time (F = 403.89, df = 11, P< 0.0001) but was not affected by exclusion treatment (F = 2.06 , df = 3, P= 0.1032) from December 1997 until July 1998 (Fig 2.7). The minimum winter temperature during this period was -14.0 °C. From November 1998 until June 1999 temperature again differed with time (F = 2118.2, df = 11, P < 0.0001) but not exclusion cage treatment (F = 1.01 , df = 3, P = 0.3874) (Fig 2.8). The minimum temperature during this period was -18.0°C.

Exclusion treatment did affect snow cover in 1997-1998 (F = 17.15, df = 3, P < 0.0001) although only five snow events totaling 51.9 cm snowfall and less than 1 d of snowcover occurred. Therefore, the effects of snow cover as temperature stabilizer (Armstrong 1994; Armstrong and Peairs 1996) were limited. Exclusion treatments affected snow cover again in 1998-1999 (F = 15.99, df = 3 , P < 0.0001), with two events totaling 14.1 cm and 3 days of snow cover (Table 2.10). The most snow was measured in the no exclusion treatment and the least in the complete exclusion treatment.

Rainfall was not affected by exclusion treatment in 1997-1998 (F =0.19, df = 2, P=0.8313) and 1998-1999 (F = 1.01, df =2, P=0.3672). The lack of cage effect may have been due to fabric type or roof design (Table 2.11).

Parasitoid counts were not affected by exclusion treatments in 1997-1998 (F = 0.81, df =3, P=0.4912) and 1998-1999 (F = 0.48, df =3, P=0.6988). Similarly, predators were not affected by exclusion treatments in 1997-1998 (F = 0.97, df =3, P=0.4112) and 1998-1999 (F = 0.48, df =3, P=0.6988). Similar results were observed both seasons for wheat genotype exclusion treatments combinations (Tables 2.12, 2.13, 2.14 and 2.15). Therefore natural enemies were not affected by exclusion treatment in 1997-1998 ($F = 0.39$, df = 3, P=0.6784) and 1998-1999 ($F = 0.13$, df = 3, P=0.8792). This may have been due to cage design, insecticide choice or generally low natural enemy activity.

More hours below 0.0°C were observed in the no exclusion treatment compared with the other exclusion treatments in 1997-1998 season (Table 2.16) but not 1998-1999 (Table 2.17). Other cage designs might have accumulated heat differentially. Also, location differences might be a reason for temperature differences between years (Table 2.16 and 2.17). The effects of accumulated temperatures above 20°C were not affected by exclusion treatment / wheat genotype combinations in either years (Tables 2.18 and 2.19).

Table 2.10. The effect of the exclusion treatment on the mean of the amount of snow received (cm) (± SEM) during 1997-1998 season and 1998-1999 season. Agricultural Research. Development and Education Center. Fort Collins. CO.

Exclusion treatments	**1997-98**	**1998-98**
Completely exclusion	0.5 ± 0.2b	0.0 ± 0.0b
Partial exclusion with and without insecticides	4.9 ± 0.5a	6.3 ± 1.0a
No exclusion	5.6 ± 0.7a	7.6 ± 0.7a
$LSD_{0.05}$	1.978	2.00
F-value	17.15	15.99
$P > F$	0.0001	0.0001

Mean within a column followed by the same letter (s) are statistically similar according to Fisher protected LSD (α=0.05).

Table 2.11. The effects of exclusion treatment on the mean of rainfall amount received (cm) (± SEM), 1997-1998 and 1998-1999. Agricultural Research, Development and Education Center, Fort Collins, CO.

Exclusion treatments	**1997-1998**	**1998-1999**
Completely exclusion	0.6 ± 0.5a	0.9 ± 0.4
Partial exclusion with and without insecticides	0.7 ± 0.6a	1.0 ± 0.3a
No exclusion	0.7 ± 0.6a	1.0 ± 0.1a
$Dunn_{0.05}$	1.9847	2.4314
F- value	0.19	1.01
P > F	0.8313	0.3672

Mean within a column followed by the same letter (s) are statistically similar according to Bonferroni Dunn (α=0.05).

Table 2.12. Effects of exclusion treatment and resistance on mean of parasitoid mummies counts (± SEM), 1997-1998, Agricultural Research, Development and Education Center, Fort Collins, CO.

Exclusion treatments							
Wheat genotypes	**Complete exclusion**	**Partial exclusion plus insecticide**	**Partial exclusion**	**No exclusion**	**$Dunn_{0.05}$**	**F-value**	**P > F**
CO 940626	3.0 ± 2.5A	1.2 ± 0.8A	0.4 ± 0.3A	4.2 ± 2.1A	4.9188	1.01	0.4031
CO 940252	0.5 ± 0.3A	1.1 ± 0.6A	2.6 ± 1.3A	1.7 ± 0.7A	2.84690	1.24	0.3139
TAM 107	0.7 ± 0.6A	0.3 ± 0.3A	4.0 ± 2.7A	1.5 ± 0.7A	2.05183	1.05	0.3875

Mean within a row followed by the same letter (s) are statistically similar according to Bonferroni Dunn (α=0.05).

Table 2.13. Effects of exclusion treatment and resistance on mean of parasitoid mummies counts (± SEM), 1998-1999, Agricultural Research, Development and Education Center, Fort Collins, CO.

Exclusion treatments							
Wheat genotypes	**Complete exclusion**	**Partial exclusion plus insecticide**	**Partial exclusion**	**No exclusion**	**$Dunn_{0.05}$**	**F-value**	**P > F**
CO 940626	5.2 ± 4.6A	4.1 ± 0.0A	3.1 ± 1.7A	1.6 ± 1.3A	2.03693	0.30	0.8274
CO 940252	4.5 ± 1.9A	0.0 ± 0.0A	0.6 ± 0.4A	0.0 ± 0.0A	2.03693	2.57	0.0716
TAM 107	1.5 ± 0.8A	1.5 ± 0.6A	0.0 ± 0.0A	1.8 ± 1.1A	2.52221	0.13	0.8743

Mean within a row followed by the same letter (s) are statistically similar according to Bonferroni Dunn (α=0.05).

Table 2.14. Effects of exclusion treatment and different wheat genotypes varying in resistance to aphids on the mean of coccinellid counts (± SEM), 1997-1998. Agricultural Research, Development and Education Center, Fort Collins, CO.

	Exclusion treatments						
Wheat genotypes	**Complete exclusion**	**Partial exclusion plus insecticide**	**Partial exclusion**	**No exclusion**	**$Dunn_{0.05}$**	**F-value**	**P > F**
CO 940626	2.1 ± 0.7A	1.4 ± 0.8A	1.8 ± 0.9A	2.6 ± 1.0A	2.6316	0.31	0.8172
CO 940252	4.0 ± 2.7A	6.0 ± 4.6A	3.0 ± 1.1A	6.0 ± 2.6A	2.05183	0.23	0.8761
TAM 107	2.0 ± 0.6A	1.8 ± 1.0A	1.6 ± 0.7A	8.7 ± 8.0A	2.05183	0.81	0.4985

Mean within a row followed by the same letter (s) are statistically similar according to Bonferroni Dunn (α=0.05).

Table 2.15. Effects of exclusion treatment and different wheat genotypes varying in resistance to aphids on the mean of coccinellid counts (± SEM), 1998-1999. Agricultural Research, Development and Education Center, Fort Collins, CO.

	Exclusion treatments						
Wheat genotypes	**Complete exclusion**	**Partial exclusion plus insecticide**	**Partial exclusion**	**No exclusion**	**$Dunn_{0.05}$**	**F-value**	**P > F**
CO 940626	3.0 ± 0.7A	2.6 ± 2.6A	2.7 ± 0.6A	2.0 ± 1.8A	2.81234	0.10	0.9604
CO 940252	4.5 ± 1.8A	2.6 ± 2.6A	2.6 ± 0.6A	0.5 ± 0.5A	2.81234	0.76	0.5259
TAM 107	3.3 ± 0.6A	3.6 ± 1.3A	0.0 ± 0.0A	0.1 ± 0.1A	2.52221	1.26	0.2968

Mean within a row followed by the same letter (s) are statistically similar according to Bonferroni Dunn (α=0.05).

Table 2.16. The mean number of hours below zero degree centigrade (± SEM) in 4 exclusion treatments with 3 wheat genotypes varying in resistance to aphids from December 1997 until March 1998, Agricultural Research, Development and Education Center, Fort Collins, CO.

Exclusion treatments						
Wheat genotypes	**Complete exclusion**	**Partial exclusion with and without insecticide**	**No exclusion**	**$LSD_{0.05}$**	**F-value**	**P > F**
CO 940626 and CO 940252	2930.0 ± 433.6B	2011.5 ± 284.2B	6252.2 ± 1062A	2183.5	10.69	0.0042
TAM 107	1889.2 ± 311.2B	2059 ± 376.2B	6309.0 ± 966.6A	2000.2	16.04	0.0011

Mean within a row followed by the same letter (s) are statistically similar according to Fisher protected LSD (α=0.05).

Table 2.17. The mean number of hours below zero degree centigrade (± SEM) in 4 exclusion treatments with 3 wheat genotypes varying in resistance to aphids from November 1998 until March 1999. Agricultural Research, Development and Education Center, Fort Collins, CO.

Exclusion treatments						
Wheat genotypes	**Complete exclusion**	**Partial exclusion with and without insecticide**	**No exclusion**	**$Dunn_{0.05}$**	**F-value**	**P > F**
CO 940626 and CO 940252	2167.7 ± 654.6A	2269.7 ± 703.2A	2404.7 ± 803.7A	3000.1	0.03	0.9734
TAM 107	2222.7 ± 717.2A	4306.5 ± 1717.4A	2430.5 ± 783.0A	4836.2	0.97	0.4157

Mean within a row followed by the same letter (s) are statistically similar according to Bonferroni Dunn (α=0.05).

Table 2.18. The accumulative mean degree hours above 20°C (± SEM) in 4 exclusion treatments with 3 wheat genotypes varying in resistance to aphids from December 1997 until March 1998, Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	**Exclusion treatments**					
	Complete exclusion	**Partial exclusion with and without insecticide**	**No exclusion**	**$Dunn_{0.05}$**	**F-value**	**P > F**
CO 940626 and CO 940252	2478.1 ± 808.7A	1510.1 ± 479.6A	3436.6 ± 1077.4A	3037.4	1.36	0.2781
TAM 107	1925.0 ± 557.6A	1706.7 ± 558.1A	4547.7 ± 1573.3A	3738.3	2.42	0.1132

Mean within a row followed by the same letter (s) are statistically similar according to Bonferroni Dunn (α=0.05).

Table 2.19. The accumulative mean degree hours above 20°C (± SEM) in 4 exclusion treatments with 3 wheat genotypes varying in resistance to aphids from November 1998 until March 1999. Agricultural Research, Development and Education Center, Fort Collins, CO.

Wheat genotypes	**Exclusion treatments**					
	Complete cage	**Partially caged with insecticide partially caged without insecticide**	**No cage**	**$Dunn_{0.05}$**	**F-value**	**P > F**
CO 940626 and CO 940252	2025.8 ± 731.5A	1360.8 ± 377.1A	2297.0 ± 853.4A	2690.8	0.50	0.6214
TAM 107	1206.0 ± 377.5A	4553.0 ± 1715.0A	2296.4 ± 858.3A	4436	2.29	0.1440

Mean within a row followed by the same letter (s) are statistically similar according to Bonferroni Dunn (α=0.05).

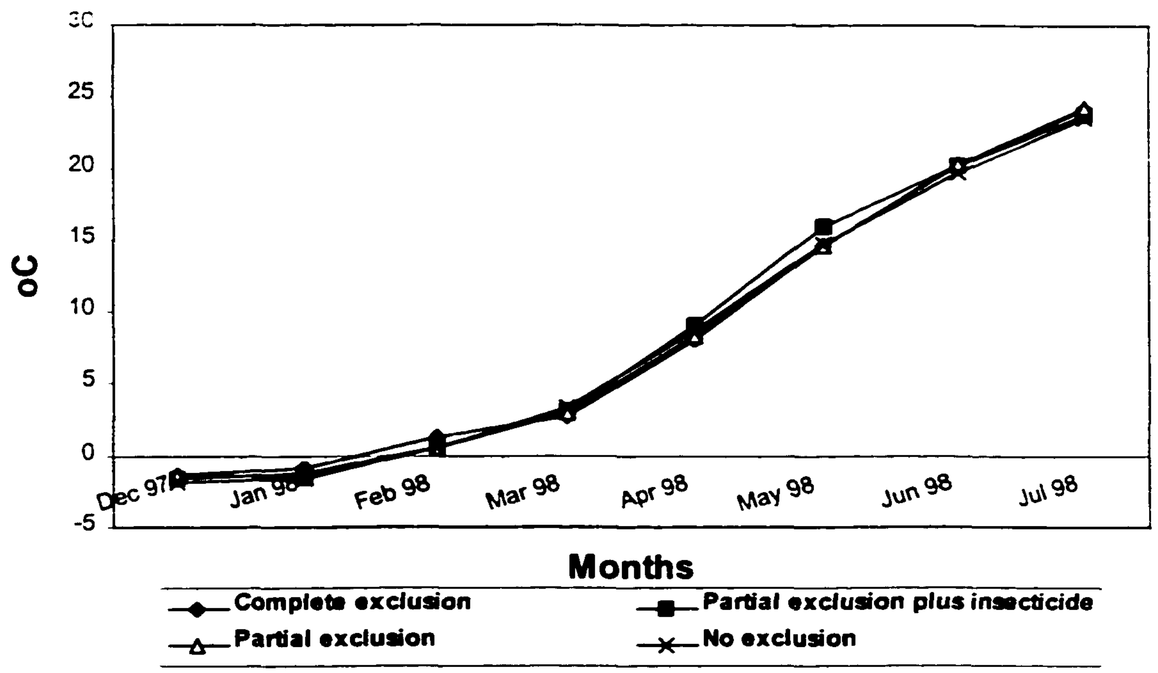

Fig 2.7. Average monthly temperatures in 4 types of exclusion cages, December 1997 - July 1998. Agricultural Research Development and Education Center, Fort Collins, CO.

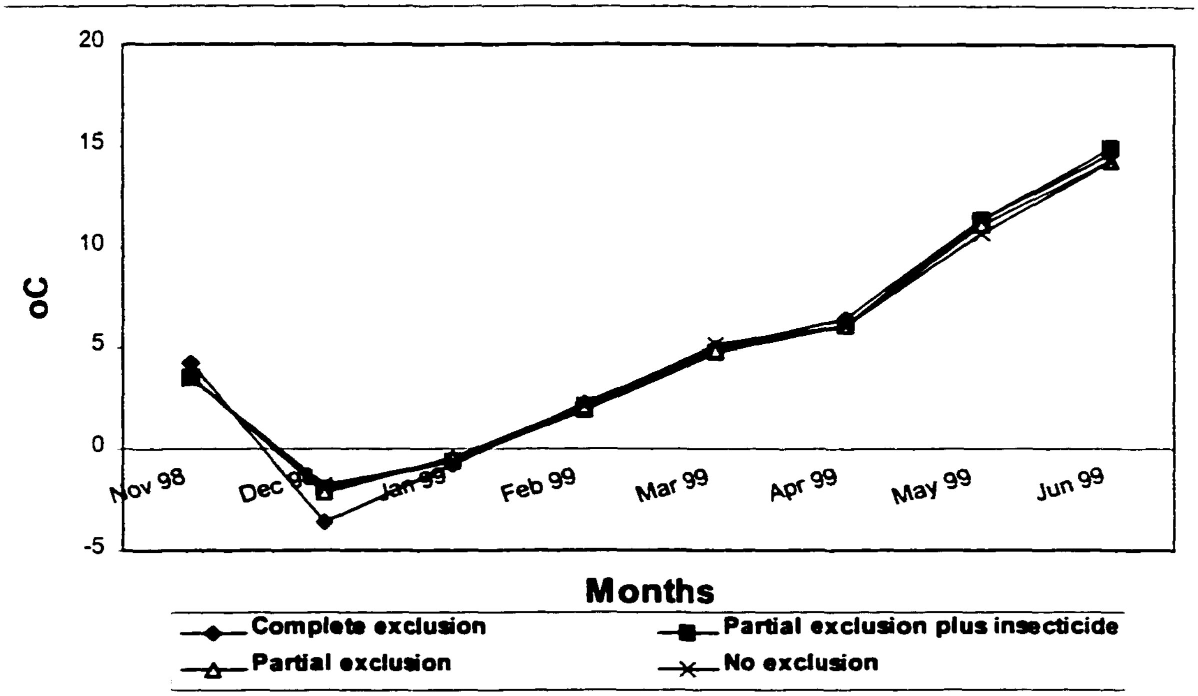

Fig 2.8. Average monthly temperatures in 4 types of exclusion cages, November 1998-June 1999. Agricultural Research, Development and Education Center, Fort Collins, CO.

Exclusion treatment did not affect amount of rainfall measured received from April-June 1998 (F = 0.19, df = 2, P = 0.8313) or April-June 1999 (F = 1.01, df = 2, P = 0.3672). In other studies simulated rain of 15 mm during 30 minutes resulted in a 58 % displacement of aphids, while natural rain resulted in a 39 % displacement of aphids (Zuniga 1982). Others studies with similar results indicate that rainfall can displace many aphids from a plant (Dhaliwal and Singh 1975). Consistent rainfall however, is important for aphid mortality. In this study, rainfall affected the Russian wheat aphid abundance in both years for only short periods of time, (3days, F = 3.11, df = 64 , P = 0.0172) (7days, F = 17.42, df = 21 , P < 0.0001) respectively. In 1997-98 there were 10 rain events from late April to early June totaling 62 mm. However, in 1998-1999 there were 13 rain events between April 22 to May 28, 1999 totaling 114 mm. Rainfall frequency and amount were important mortality factors. Rainfall affected the interaction of wheat genotype and aphid abundance in both years 1997-1998 (F = 3.31, df = 4, P= 0.0927) and 1998-1999 (F = 2.39 , df = 4, P= 0.0600) respectively. These results were similar those of Liang et al. (1998) and Legg and Brewer (1995).

Russian wheat aphid density was not affected by *D. rapae* parasitoids in 1997-1998 season (F = 0.02, df = 1, P = 0.8969) but effects were observed in 1998-1999 (F = 102.28, df = 1, P < 0.0001). Wheat genotype did not affect *D. rapae* abundance in 1997-1998 (F = 0.21, df = 2, P = 0.8119) or 1998-1999 (F = 2.15, df = 2, P = 0.1228), consistent with Brewer et al. (1998) observations on barley. No differences were observed between the partial exclusion with insecticide and partial exclusion without insecticide treatments for parasitoids or predators in either year.

Regression model for 1997-1998 and 1998-1999 season. Winter phase.

In comparing the model statistics for the additive effects of independent variables over the 2 years of the study, the accumulated degree hours < 0 °C (AH0) alone resulted in R^2 =0.62 and CP= 0.78 for Russian wheat aphid on the resistant wheats (Table 2.20). Also R^2 =0.63 and a higher CP= 2.62 was noted for Russian wheat aphid totals on TAM 107, indicating that low temperatures affected Russian wheat aphid more on resistant wheats than on the susceptible under no cage treatment for both years.

The AH0 was related to Russian wheat aphid decline (Table 2.20). This might be different if more snowcover duration had occurred. Snowcover duration was limited in both years compared to Armstrong and Peairs (1996) when more than 40 days of snowcover was reported, stabilizing subnivean temperatures. Also, the curled leaves on TAM 107 might insulate aphids (Armstrong 1994). However, aphids on both resistant and susceptible wheats were affected similarly by the number of hours below zero. However, the limited number of snow events and mild temperatures during the study period may have limited wheat genotype effects on Russian wheat aphid survival. Also, host genotype effects on Russian wheat aphid overwintering might be reduced by holocycly, since the eggs is the most cold tolerant stage.

Regression model for 1997-1998 and 1998-1999 season. Spring phase.

Natural enemy activity was the most important independent variable in several exclusion-genotype combinations (Table 2.21). Natural enemies affected Russian wheat aphid more on TAM 107 and partial exclusion than on other treatment combinations R^2= 0.97, CP = 1.21, P = 0.0001, (Table 2.21). This consistent with the observations reported in Chapter 1. Thus, unrolled leaf structure had no effect on the performance of Russian wheat aphids parasitoids. Although Kauffman and La Roche (1994), concluded that leaf rolling hindered the performance of coccinellids under lab condition, Brewer et al. (1998) and this study showed leaf rolling had no effect on natural enemies activities based on the higher P-value and R^2 (Table 2.21).

Average daily rainfall (ADRF) affected Russian wheat aphid density only on the resistant wheats (Table 2.21). Rain displacement of the aphid on uncurled leaves is evidenced by the negative correlation of *D. noxia* and rainfall between March - Jun in both years, similar to Liang et al. (1998) observations in China. Rainfall is thus more important Russian wheat aphid mortality factor on wheats resistant to leaf rolling. This might answer the concerns of Legg and Brewer (1995) regarding the impact of rainfall on Russian wheat aphid abundance in dryland winter wheat production areas.

The accumulated degree hours above 20°C affected Russian wheat aphid abundance negatively (Table 2.21). Michels and Behle (1989) observed that Russian wheat aphids populations declined in the lab under 19-25 °C temperature regime. More temperature accumlation might occur in the curled leaf due to the restricted air movement.

Table 2.20. Best-fit linear regression models for Russian wheat aphid densities on resistant and susceptible wheats in different exclusion cages versus accumulated degree hours < 0 °C (AH0) December-March 1997 -1998 and November 1998 - April 1999. Agricultural Research, Development and Education Center, Fort Collins CO.

Wheat genotype	Cage Treatment	Independent variables	Intercept	Slope	R^2	CP	F	P
CO 940626,CO940252	No cage	AH0	-0.11	0.85	0.62	0.78	9.93	0.0198
TAM 107	No cage	AH0	-0.04	0.49	0.63	2.62	10.52	0.0176

[a] All possible models presented in appendix B.

Table 2.21. Best-fit linear regression models (a) for Russian wheat aphid densities on resistant and susceptible wheats in different exclusion cages versus natural enemies (parasitoids and predators) (NE), average daily rain fall (ADRF) and accumulative degree hours < 20 °C (ADH20). March-June 1997-1998 season and April June 1998-1999. Agricultural Research, Development and Education Center, Fort Collins CO.

Wheat genotypes	Cage Treatment	Independent variables	Intercept	Slope	R^2	CP	F	P
CO 940626, CO940252	Partially caged	NE	9.19	0.21	0.39	2.67	4.49	0.0718
TAM 107	Partially caged	NE	-2.06	0.68	0.97	1.21	257.24	0.0001
CO 940626, CO940252	No cage	NE	5.24	0.17	0.91	11.41	80.03	0.0001
CO 940626, CO940252	No cage	ADRF	5.24	-9.95	0.95	7.05	3.80	0.0993
TAM 107	No cage	NE	8.56	0.41	0.97	12.59	305.44	0.0001
TAM 107	No cage	ADH20	8.56	-0.05	0.98	6.43	5.19	0.0629

[a] All possible models presented in appendix B.

Conclusions

Russian wheat aphid population densities were affected by wheat genotype. Exclusion cages prevented snowfall but did not result in differences in temperature or rainfall. Malathion did not affect parasitoid and predator activity under partial exclusion. This might have been due to unexpected tolerance of these natural enemies to malathion or insufficient exposure. Natural enemies were not affected by wheat genotypes. Accumulated freeze hours affected the Russian wheat aphid negatively on both resistant susceptible wheats. Russian wheat aphids are more abundant in low rainfall and rainfall affected Russian wheat aphid more on resistant wheats. High temperatures affected Russian wheat aphid more on wheat with rolled leaves. These negative effects of rainfall and cold temperatures may explain partially the relatively low abundance of Russian wheat aphid on resistant plants commonly observed under field conditions.

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Chapter 3

Characterization of resistance to Russian wheat aphid, *Diuraphis noxia* (Mordvilko), in two resistant wheat genotypes

Introduction

Russian wheat aphid, *Diuraphis noxia* (Mordvilko), is a major insect pest of small grains in western United States and Canada. Russian wheat aphid spread rapidly across the western United States since its discovery, causing major economic losses. Direct losses have ranged from $129.3 million in 1988 to $6.4 million in 1991. From 1987 to 1993, estimated direct losses were $432.5 millions (Morrison and Peairs 1998).

Insect control strategies are based on benefit analyses for specific crop production system and the pest being regulated. Quisenberry and Schotzko (1994a) concluded that insect resistant cultivars are an environmentally and economically acceptable strategy that integrates well with other integrated pest management strategies.

Host plant resistance to insects has been defined by Painter (1951) As " the relative amount of heritable qualities possessed by a plant which influence the ultimate degree of damage done by the insect in the field". Painter classified this resistance into three categories: antibiosis, nonpreference and tolerance. Kogan and Ortman (1978) recommended that nonpreference be termed antixenosis. Antibiosis is the properties of a plant that directly or indirectly affect pest biology (survival, growth, development or fecundity). Antibiosis includes adverse effects of chemical or morphological defense mechanisms of the plant, and may range in severity from minimal impact to death of an insect (Smith 1989). Antixenosis is the host properties affecting the insect as it seeks food, shelter or oviposition sites, resulting in a plant that is avoided or less colonized (Quisenberry and Schotzko 1994a). Sometimes antibiosis and antixenosis effects cannot be separated (Panda and Khush 1995). Tolerance is the ability of the plant to withstand.

reproduce or recover from an insect population that otherwise would damage a susceptible plant (Panda and Khush 1995). These three categories often interact or compensate for each other. Therefore, different cultivars may exhibit the same overall level of resistance through expression of different combinations of these categories. An understanding of the resistance categories expressed by a cultivar is needed to determine its utility in insect pest management (Panda and Khush 1995; Smith 1989).

Russian wheat aphid resistance in wheat was first reported in South Africa (Butts and Pakendorf 1984). Additional resistance to *D. noxia* was identified in *Triticum aestivum* lines from the former Soviet Union (PI 262660)(du Toit 1987), Iran (PI 137739) and Bulgaria (PI 294994) (du Toit 1988). Resistance in PI 137739 and PI 262660 was attributed to antixenosis and a low level of antibiosis (du Toit 1987; Quisenberry and Schotzko 1994b; Smith et al. 1992). Ni and Quisenberry (1997) confirmed that resistance in PI 137739 (Dn1) was attributed to antixenosis based on aphid probing behavior and leaf surface structure. Resistance in PI 262660 (Dn2) was expressed as tolerance and antibiosis (du Toit 1989; Smith et al. 1992). Low levels of tolerance and antibiosis were found in PI 294994 (Dn2) (Smith et al. 1992). Unger and Quisenberry (1997) found that PI 47545, PI 94355, PI 94365, PI 151918, PI 225245, PI 225262 were antibiotic to *D. noxia*.

Many procedures and experiments have been designed to categorize resistance (Panda and Khush 1995; Smith 1989). Antixenosis can be measured in free choice tests. Insects are released in an arena containing test plants and observed as to where they establish (Hawley 1997; Panda and Khush 1995).

Antibiosis is tested under no choice conditions. Plants are planted, infested and caged individually. Fecundity, adult longevity, egg hatchability, population increase and metabolic utilization of ingested food have been used to evaluate cereal antibiosis to insects (Smith et al. 1994). Webster et al. (1987) counted and removed nymphs produced by individual apterous adult Russian wheat aphids. Fecundity, nymph production, nymphipoitional period, and adult Russian wheat aphid longevity were used by Smith et al. (1992) to identify antibiosis. Lamb and Mackay (1995) proposed aphid biomass production as a more effective measure of antibiosis than fecundity. Smith et al. (1992) and Quisenberry and Schotzko (1994b) stressed that aphids should be preconditioned for at least three generations on the wheats on which they were to be evaluated for antibiosis to avoid any maternal effects.

Tolerance is usually identified by comparing plant damage, stand, plant biomass production or yield of infested and uninfested plants (Smith et al. 1994). It is very difficult to quantify tolerance separately from antibiosis and antixenosis because they often occur in combination (Reese et al. 1994). Tolerance indices, based on height and weight of infested and uninfested plants were used to measure *D. noxia* tolerance in barley (Robinson et al. 1991). Biomass conversion (i.e. biomass reduction in plant tissue per unit of biomass gained by the aphid) also has been used to estimate tolerance (Lamb and Mackay 1995). This ratio provided a method for quantifying and separating tolerance and antibiosis to aphids in cereals.

Categorization of antibiosis and tolerance is time consuming, e.g. Unger and Quisenberry (1997) took 84 days to measure antibiosis by counting nymphs daily until the aphid adult died. However, Lamb and Mackay (1995) stated that both antibiosis and tolerance could be quantified only within 6 days after infestation of test plants.

My objective in this study was to categorize the resistance CO 940626 and CO 940252 wheats to the Russian wheat aphid using the regular procedure for antixenosis (Panda and Khush 1995) and the Lamb and Mackay (1995) procedure for antibiosis and tolerance, extending the test period to nine days as recommended by Budak (1998).

Materials and Methods

Plant materials.

Three wheat lines were used in this experiment: (1) CO 940626 (CO 850034/T-57//5* TAM 107) containing the Dn4 resistance gene; (2) CO 940252 (TAM 107//PI243781/CO850260) containing the Dn6 resistance gene; and (3) the susceptible wheat 'TAM 107' (J. S. Quick, Department of Soil and Crop Sciences, Colorado State University, personal communication).

Aphid colony.

The *D. noxia* colony used to infest the antixenosis experiment was started from aphids collected from eastern Colorado in August 1997 and was reared on a mixture of susceptible wheat and barley. The antibiosis and tolerance experiments were infested from a colony started with aphids collected from Agricultural Research, Development and Education Center (ARDEC) in August 1998 (J. Rudolph, Department of Bioagricultural Science and Pest Management, Colorado State University, personal communication). Colonies were maintained on a mixture of susceptible wheat and barley under greenhouse conditions. Aphids used in antibiosis and tolerance experiments were preconditioned for at least 6 generations on the wheat to be tested (Quisenberry and Schotzko 1994b: Schotzko and Smith 1991; Smith et al. 1992).

General procedures for test plants.

Seeds were germinated in petri dishes and then vernalized at a cold room at 1°C for eight weeks. Vernalized plants were grown in a three part soil, two part perlite and one part peat moss potting soil mixture. Vernalized seeds were planted individually into

'SC-10 Super Cell' single cell "cone-tainers" (3.81 cm diameter by 21 cm depth)(Stuewe & Sons, Inc. Corvallis, Oregon). "Cone-tainers" were held in 7 x 14 "Cone-tainer" trays with open slots between each consecutive "Cone-tainer" to provide light. All experiments were conducted in a growth chamber (Sherer Control Environment Lab, Sherer-Gillett CO., Marshall. Michigan) set for 22±0.2°C 16:8 (L:D) photo period and > 50% RH.

Antixenosis: Procedures.

The experimental arena was a petri dish 100 x 25mm (Falcon, Becton Dickinson and Company, NJ) bottom with nine notches around the top. Two thick rubber bands were placed around the petri dish so that only a small slit appeared at each notch. A portion of the rubber band covered the notches to prevent aphid escapes. In the center of the arena was a smaller petri dish, 60 x 15mm (Falcon, Becton, Dickinson and Company, NJ) filled with floral clay in which test leaves were placed. A petri dish lid with the rim removed was placed over the floral clay to hold test leaves in place.

At seedling growth stage 13 (Zadoks et al. 1974), the most recently emerged leaf (still attached to plant) of each plant was threaded through one of the slits in the side of the arena (3 leaves per wheat). Leaf tips were placed in the floral clay. Ninety adult Russian wheat aphids were released (10 per leaf) in the center arena. Russian wheat aphids present on each leaf were counted 48 h after infestation.

Antixenosis: Experimental design.

The design was a randomized complete block with 9 replicates, repeated twice (Steel and Torrie 1980) (Table 3.1).

Antixenosis: Data analysis.

Trials were combined together after testing for trial effect (F= 0.97, df=1, P=0.3277). Data were analyzed for the effect of different wheat genotypes with PROC GLM (SAS 1996) and means were separated by using Fisher's protected LSD test (α=0.05) (Little and Hills 1987).

Table 3.1: Analysis of variance for randomized complete block experiment design.

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	F
Total	53	SS Total		
Block	8	SS Block	MSR	F_{Reps}
Wheat line	2	SSWheat	MSWheat	$F_{wheat\ line}$
Trial	1	SSTrial	MSTrial	F_{trial}
BlockxwheatxTrial	40	SSE	MSE	

The following model was applied :

$$Y_{ijk} = M + \rho P_k + A_i + \beta B_j + T_t \ (AB\beta T)_{ijt} + \Sigma E_{ijtk}$$ (Steel and Torrie 1980).

i = Wheat variety. , j = Russian wheat aphids. k = block effect 1.......6.. T = Trial.

Antibiosis and tolerance: Procedures.

At the beginning of each trial, the height and above-ground dry weights of 20 seedlings of each wheat were measured. Dry weight was determined by cutting the plant at the soil surface, placing it in a paper bag, drying it at 75°C for 48 h. and then weighing the plant. Three groups of 60 preconditioned adult aphids for each wheat were dried at 75°C for 24 h and weighed to be used as a constant for adult dry weight.

Zadoks 13 growth stage plants were grouped in threes according to height and one member of each group was infested with 2 preconditioned adult aphids and a second with 4 preconditioned aphids, using a camel hair brush. The third plant was left uninfested but was touched with the brush. Each plant was covered with a transparent tube cage (3.9 cm diameter by 30 cm height) constructed from clear overhead projection film(C Line Production. Inc, N. J). Six groups of plants per wheat were used per trial. The trial was repeated twice. After 9 d aphids were removed, counted and placed in pre- weighed glass vials (14.5 x 45 mm) containing 95% ethanol. Aphids were then dried in the vials at 75°C for 24 h. and weighed. Aphid weight was determined by subtracting the vial pre-weight from vial plus dry aphid weight. Plant heights and dry weights were determined as described above. Tolerance was estimated using the indices below (Lamb and Mackay 1995; Robinson et al. 1991), and antibiosis was determined by final aphid number, aphid fecundity and aphid biomass (Lamb and Mackay 1995). The following formulas were used:

Antibiosis

$$\text{Aphid fecundity} = \frac{\text{Final number of the aphids - Initial infestation density}}{\text{Initial infestation density (2 or 4)}}$$

Aphid biomass = Final aphid biomass - Calculated adult dry weight (aphid weight at the beginning of each trial)

Plant biomass = Plant dry weight (Control) - Plant dry weight (Infested)

Tolerance

Index A (Biomass conversion ratio) = Plant biomass ÷ Aphid biomass (Lamb and Mackay 1995)

Index B= Plant biomass ÷Aphid dry weight x plant dry weight (Control) x 100 (Robinson et al. 1991)

Index C= Plant height (Control)-Plant height (infested)÷ Aphid dry weight x plant height (Control) (Robinson et al. 1991)

Antibiosis and tolerance: Experimental design.

Experimental design was a randomized complete block with factorial analysis with three wheats (TAM 107, CO 940626, CO 940252) and three aphid densities (0,2,4) with six replicates (Steel and Torrie 1980) (Table 3.2).

Table 3.2: Analysis of variance for a two - factor treatment design in randomized complete block experiment design.

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	F
Total	14	SS Total		
Block	5	SS Block	MSR	F_{Reps}
Trial	1	SS Trial	MSR	F_{Trials}
Aphid level	2	SSaphids	MSAphids	$F_{aphid\ level}$
Wheat line	2	SSWheat	MSWheat	$F_{wheat\ line}$
Aphid level x wheat line	4	SS(Aphids* Wheat)	MS(Aphids* Wheat)	$F_{aphidsxwheat\ line}$

The following model was applied :

$$Y_{ijk} = M + \rho P_k + A_i + \beta B_j + T_t + (AB\beta)_{ijt} + \Sigma E_{ijtk} \text{(Steel and Torrie 1980)}$$

i = Wheat variety. , j = Russian wheat aphid level of infestations (0, 2 and 4).. k = block effect 1.......6.

Antibiosis and tolerance: Data analysis.

Trial effect was tested before combining the two trials. Aphid fecundity (F=29.38, df=1, P< 0.0001) and aphid biomass (F=79.68, df=1, P<0.0001) were treated separately with each trial. Other variables were combined. The PROC GLM procedure (SAS 1996) was used for analysis of aphid fecundity, aphid biomass, plant biomass, Index A, plant dry weight and plant heights. Means were compared by protected Fisher's LSD method if P>F was <0.05 and by Bonferroni's method if P>F >0.05. The PROC MIXED and

LSmeans procedure (SAS 1996) were used to analyze Index B and Index C (P. Chapman, Department of Statistics, Colorado State University Personal communication).

Results and Discussion

Antixenosis.

Antixenosis, was detected in both CO 940626 and CO 940252 at seedling growth stage 13 Zadoks (Table 3.3). Aphid counts were not similar among wheats (F=17.61, df = 2, P< 0.0001). CO 940626 had fewer aphids than CO 940252 indicating that Dn4 expressed more antixenosis than Dn6. Detection of antixenosis in both wheat genotypes raises the possibility of morphological or chemical plant factors that adversely alter insect behavior which result in selection of an alternate host plant. Hawley (1997) observed antixenosis in 'Halt', a Dn4 line, at Zadoks 30 but not Zadoks 13.

Russian wheat aphid might be subjected to selection pressure from this particular wheat genotype. There are limited reports of antixenosis in lines containing Dn6. However, both wheat genotypes could be an important factor in encouraging the development of Russian wheat aphid biotype because of the selection pressure.

Table 3.3. Mean (±SEM) adult *D. noxia* on 3 wheats differing in resistance to Russian wheat aphid after 48 h of free choice test, averaged over 2 trials.

Wheat genotypes	**Aphids Per leaf***
CO 940626	7.6 ± 0.6c
CO 940252	11.0 ± 0.6b
TAM 107	14.0 ± 1.1a
$LSD_{0.05}$	2.0119
F- value	17.61
P > F	0.0001

*Mean within the column followed by the same letter (s) are statistically similar according to Fisher protected LSD (α=0.05). .

Antibiosis.

Aphid final density was affected by plant genotype (F = 5.14 , df=2, P= 0.0076) (Table 3.4) and by initial aphid density (F = 28.48 , df=2, P< 0.0001) (Table 3.5). There was no interaction between wheat genotype and initial aphid density (F = 1.25 , df=4, P= 0.2948). The lowest aphid final densities were observed on the two resistant wheats compared with the susceptible.

Aphid fecundity was affected by wheat genotype (F = 3.32 , df=2, P= 0.0463) (Table 3.6) and by initial infestation density (F = 12.95 df=2, P<0.0001) (Table 3.7) in first trial. There was no interaction between initial aphid density and wheat genotype observed after 9 days (F = 0.92, df=4, P=0.4619). In the second trial wheat genotype did not affect fecundity (F = 0.36 df=2, P=0.6968) (Table 3.8), but differences due to infestations level were detected (F = 7.76 df=2, P=0.0014) (Table 3.9). No statistical interaction between aphid level and wheat genotype was detected (F = 60.83 df=4. P=0.5155). The possible explanation for the difference in fecundity between the two trials, might be due to population densities. Final density in the first trial was 8 times more than in the second trial, perhaps due to some unknown temperature fluctuations.

The aphid cohort dry weight measured prior to the experiment varied by genotype: CO 940626 0.3 mg per 60 aphids (n = 3); CO 940252 0.3mg per 60 aphids (n = 3) and TAM 107 1.3 mg per 60 aphids (n = 3). This approximately 77% reduction in weight for preconditioned aphids between resistant and susceptible wheats indicates antibiosis for both Dn4 and Dn6. Aphid biomass was affected by wheat in first trial (F = 2.79. df=2. P= 0.0731) (Table 3.10) and second trial (F = 2.48, df=2. P= 0.0964) (Table 3.11). In the second trial Russian wheat aphids gained more mass on TAM 107 than on the two resistant wheats. Total aphid biomass was higher when initial density was 4 aphids per plant (1.98 mg) than 2 aphids per plant (0.68 mg), which is consistent with Budak (1998). No statistical interaction between wheat genotypes and initial aphid density was observed in the first trial (F = 0.99 df=4, P=0.4256) but there was interaction in the second trial (F = 2.19 df=4, P=0.0879).

Reduction in final aphid number, final aphid fecundity and biomass of aphid produced were good indicators of antibiosis (Budak 1998 ; Lamb and Mackay 1995). Therefore, the resistance mechanism in both CO 940626 and CO 940252 was expressed as antibiosis against *D. noxia* at 13 growth stage after nine days of infestation. Antibiosis effects can be due to either chemical or morphological plant defenses. Hawley (1997) did not observe antibiosis for Dn4 in 'Halt' but that might be due to the different experimental methods or genetic material. The antibiosis resistance category in useful integrated pest management but, since it increase the possibility of developing aphid biotypes it should be used in combination with other strategies. Further more, chemical analysis and electronic microscopy investigation for plant leaves should be conducted to elucidate the underling causes for this antibiosis.

Table 3.4. Mean (±SEM) Russian wheat aphids per plant on 3 wheats differing in resistance to aphids, averaged over 2 initial aphid densities.

Wheat genotypes	Aphids per plant*
CO 940626	12.0 ± 2.3b
CO 940252	9.6 ± 1.6b
TAM 107	19.7 ± 4.1a
$LSD_{0.05}$	6.5381
F- value	5.14
P > F	0.0076

*Means followed by the same letter (s) are statistically similar according to Fisher protected LSD (α=0.05).

Table 3.5. Mean (±SEM) of Russian wheat aphids per plant at 2 levels of initial infestation, averaged over 3 wheat genotypes.

Infestation levels (aphids per plant)	Aphids per plant*
0	0.5 ± 0.3c
2	15.6 ± 2.2b
4	25.2 ± 3.6a
$LSD_{0.05}$	6.5381
F- value	28.48
P > F	0.0001

*Means followed by the same letter (s) are statistically similar according to Fisher protected LSD (α=0.05).

Table 3.6. Mean (±SEM) of Russian wheat aphids adult fecundity on 3 wheats differing in resistance to Russian wheat aphids, averaged over 2 initial densities, first trial.

Wheat genotypes	**Final aphid fecundity per female***
CO 940626	4.6 ± 1.4ab
CO 940252	3.3 ± 0.9b
TAM 107	6.2 ± 2.2a
$LSD_{0.05}$	3.7885
F- value	3.32
P > F	0.0463

*Means followed by the same letter (s) are statistically similar according to Fisher protected LSD (α=0.05).

Table 3.7. Mean (±SEM) Russian wheat aphid adult fecundity at two levels of initial infestation, averaged over 3 wheat genotypes, first trial.

Infestation levels (aphids per plant)	**Final aphid fecundity per female***
0	0.0 ± 0.0b
2	7.0 ± 1.8a
4	9.1 ± 1.6a
$LSD_{0.05}$	3.7885
F- value	12.95
P > F	0.0001

*Means followed by the same letter (s) are statistically similar according to Fisher protected LSD (α=0.05).

Table 3.8. Mean (±SEM) Russian wheat aphid adult fecundity on 3 wheats differing in resistance to Russian wheat aphid, averaged over 2 initial densities, second trial.

Wheat genotypes	**Final aphid fecundity per female***
CO 940626	0.7 ± 0.1a
CO 940252	1.1 ± 0.6a
TAM 107	0.9 ± 0.2a
$Dunn_{0.05}$	1.2202
F- value	0.36
P > F	0.6968

*Means followed by the same letter (s) are statistically similar according to Bonferroni (Dunn) (α=0.05).

Table 3.9. Mean (±SEM) Russian wheat aphid adult fecundity at 2 levels of initial infestation, averaged over 3 wheat genotypes, second trial.

Infestation levels (aphids per plant)	**Final aphid fecundity per female***
0	0.0 ± 0.0c
2	1.0 ± 0.1a
4	1.9 ± 0.5a
$LSD_{0.05}$	0.9869
F- value	7.76
P > F	0.0014

*Means followed by the same letter (s) are statistically similar according to Fisher protected LSD (α=0.05).

Table 3.10. Mean (±SEM) Russian wheat aphid biomass gain (mg) on wheats differing in resistance to Russian wheat aphids. averaged over 2 initial densities. first trial.

Wheat genotypes	Aphid biomass gain (mg)*
CO 940626	0.8 ± 0.5a
CO 940252	0.2 ± 0.1a
TAM 107	-0.1 ± 0.3a
$Dunn_{0.05}$	1.1275
F- value	2.79
P > F	0.0731

*Means followed by the same letter (s) are statistically similar according to Bonferroni (Dunn) (α=0.05).

Table 3.11. Mean (±SEM) Russian wheat aphid biomass gain (mg) on 3 wheats differing in resistance to Russian wheat aphids, averaged over 2 initial densities. second trial.

Wheat genotypes	Aphid biomass gain (mg)*
CO 940626	8.9 ± 2.2a
CO 940252	7.1 ± 1.5a
TAM 107	12.2 ± 3.1a
$Dunn_{0.05}$	4.6175
F- value	2.48
P > F	0.0964

*Means followed by the same letter (s) are statistically similar according to Bonferroni (Dunn) (α=0.05).

Tolerance.

Plant growth was affected by Russian wheat aphid feeding. Initial plant heights and weights varied among wheats (Table 3.12). Final plant height differences were observed among wheats (F = 5.70, df=2, P= 0.0046) and among different initial infestations (F = 21.42, df=2, P< 0.0001) (Tables 3.13 and 3.14). Both CO 940626 and CO 940252 were taller (either infested or uninfested) than TAM 107. That can be an indication of tolerance since both resistant wheats withstood Russian wheat aphid feeding. There was no statistical interaction for plant height between initial infestation density and wheat genotype (F = 0.72, df=4, P= 0.5830).

Plant dry weight was affected by wheat genotype (F = 10.49, df=2, P<0.0001) (Table 3.15). Initial infestation level did affect plant weight (F = 7.30, df=2, P= 0.0011) (Table 3.16). Only CO 940626 withstood Russian wheat aphid feeding and the other wheat genotypes were affected by aphid feeding. No statistical interaction for plant weight between wheat genotype and infestation was observed (F = 0.48, df=4, P= 0.7481). Plant biomass was affected by wheat genotype (F = 3.67, df=2, P= 0.0312) (Table 3.17), but not by initial infestation level (F = 1.57, df=2, P= 0.2156).

Robinson et al. (1991), Lamb and Mackay (1995) and (Budak 1998) used indices to estimate tolerance. However, in this study none of the 3 indices was affected by wheat genotype (Index A, F = 1.33, df=2, P= 0.2723) (Index B, F = 1.56, df=2, P= 0.2185) and (Index C, F = 0.42, df=2, P= 0.6556) (Table 3.18), even though plant height and plant dry weight reductions both were affected by wheat genotype. Finally, there was more indication of tolerance expression in CO 940626 than with CO 940252 based on plant dry weight and plant biomass reductions which was consistent with the expression of tolerance by Dn4 in 'Halt' wheat observed by Hawley (1997).

Table 3.12. Plant heights and dry weights of three wheats prior to infestation with Russian wheat aphids.

Wheat genotypes	**Plant ht. (cm)**	**Plant dry wt. (mg)**
CO 940626	14.0	29.1
CO 940252	11.3	15.7
TAM 107	13.3	43.9

Table 3.13. Mean (±SEM) Russian wheat aphid reduction on plant heights (cm) of 3 wheats differing in levels of resistance, averaged over 2 initial infestation levels.

Wheat genotypes	**Plant heights (cm)***
CO 940626	25.1 ± 0.5a
CO 940252	25.1 ± 0.6a
TAM 107	23.0 ± 0.7b
$LSD_{0.05}$	1.4118
F- value	5.70
P > F	0.0046

*Mean within a column followed by the same letter (s) are statistically similar according to Fisher protected LSD (α=0.05).

Table 3.14. Mean (±SEM) Russian wheat aphid reduction (cm) on plant heights of 2 initial infestation, averaged over 3 wheat genotypes.

Infestation levels	**Plant height (cm)***
0	27.0 ± 0.5a
2	23.3 ± 0.5b
4	22.8 ± 0.6b
$LSD_{0.05}$	1.4118
F- value	21.42
P > F	0.0001

*Mean within a column followed by the same letter (s) are statistically similar according to Fisher protected LSD (α=0.05).

Table 3.15. Mean (±SEM) reduction in plant dry weight (g) by Russian wheat aphid on 3 wheats differing in aphid resistance, averaged over 2 initial infestation levels.

Wheat genotypes	**Plant dry weight (mg)***
CO 940626	73.9 ± 6.0a
CO 940252	52.8 ± 3.0b
TAM 107	51.0 ± 3.8b
$LSD_{0.05}$	11.027
F- value	10.49
P > F	0.0001

*Mean within a column followed by the same letter (s) are statistically similar according to Fisher protected LSD (α=0.05).

Table 3.16. Mean (±SEM) reduction in Plant dry weight (g) by Russian wheat aphid in 2 initial infestation, averaged over 3 wheats differing in aphid resistance.

Infestation level	**Plant dry weight (mg)***
0	70.9 ± 4.9a
2	56.4 ± 4.2b
4	50.3 ± 4.5b
$LSD_{0.05}$	11.027
F- value	7.30
P > F	0.0011

*Mean within a column followed by the same letter (s) are statistically similar according to Fisher protected LSD (α=0.05).

Table 3.17. Mean (±SEM) reduction in plant biomass by Russian wheat aphid on 3 wheats differing in aphid resistance, averaged over 2 initial infestation levels.

Wheat genotypes	**Plant biomass (mg)***
CO 940626	17.8 ± 4.1a
CO 940252	7.7 ± 1.7b
TAM 107	9.5 ± 2.9b
$LSD_{0.05}$	11.994
F- value	3.67
P > F	0.0312

*Mean within a column followed by the same letter (s) are statistically similar according to Fisher protected LSD (α=0.05).

Table 3.18. Mean (±SEM) Tolerance indices for 3 wheats differing in resistance to Russian wheat aphid, averaged over 2 initial infestation levels.

Wheat genotypes	**Index A***	**Index B***	**Index C****
CO 940626	-27.6 ± 27.4	22.9 ± 12.1	5.9 ± 3.3
CO 940252	6.6 ± 5.4	5.0 ± 3.8	11.9 ± 4.7
TAM 107	3.0 ± 2.2	6.7 ± 4.8	8.5 ± 5.6
F - value	1.33	1.56	0.42
P-value	0.2723	0.2185	0.6556

* (Robinson et al. 1991).
**(Lamb and Mackay 1995)

Conclusions

Antixenosis was detected in both resistant genotypes at Zadoks growth stage 13. Antibiosis as measured by final aphid density, aphid fecundity and aphid biomass were expressed in both CO 940626 and CO 940252. This supports the observations of low field densities reported in Chapter 1. Initial plant heights and weights among different wheat genotypes were too variable to allow effective use of the tolerance indices. Some tolerance expression was observed in the Dn4 line in the form of less plant dry weight and biomass reduction.

Similar studies should be conducted over longer time extensions and greater aphid infestation levels. Both resistant genotypes need further studies of morphological and chemical characteristics because of the evidence for both antixenosis and antibiosis.

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Overall Summary

Resistant wheats had low aphid densities compared to the susceptible wheats. Both CO 940626 and CO 940252 appeared antibiotic during the three years field study. In support of the field study both antixenosis and antibiosis were clearly detected in both wheat genotypes in the laboratory. The antibiosis resistance category was expressed by an increased proportion of Russian wheat aphids first instar compared to the susceptible cultivar TAM 107. Also delays were observed in expressing wheat genotypes effects this age class structure perhaps due to maternal effects. The antixenosis resistance category also was clearly indicated in the lab experiment. Little evidence for tolerance was obtained from the lab experiment, but the presence of this resistance category could not be completely excluded.

Parasitoid mummies were observed more on TAM 107 that on the two resistant wheats indicating that curling leaves does not prevent parasitization. Both resistant wheats had flat leaves which allow for more effective natural enemy searching. Predator and parasitoid activity was not affected by malathion.

Accumulated freeze hours affected Russian wheat aphid abundance negatively on both resistant and susceptible wheats. On the other hand, high temperature affected Russian wheat aphids more on rolled leaves susceptible wheat than resistant wheats.

As one of the most important finding was the effects of rainfall on Russian wheat aphid on leaf rolling resistant wheats. This might explain partially the lower abundance of Russian wheat aphid higher rainfall regains.

Quality of seeds in CO 940626 and TAM 107 were affected by high infestation level. Grain protein increases observed with TAM 107 might be due to aphid stress or lowered test weight to aphid damage.

Glossary

Anholocyclic. Life cycle strategy, vivaparae are produced throughout the year, and there is no sexual reproduction.

Holocyclic. Life cycle strategy were reproduction is accomplished sexually during the fall and parthenogenetically (Viviparity) from the spring to the next fall.

Antibiosis. The properties of a plant that directly or indirectly affect pest biology (survival, growth, development or fecundity).

Antixenosis (nonpreference). The host plant properties affecting the insect as it seeks food, shelter or oviposition sites, resulting in a plant that is avoided or less colonized.

Tolerance. The ability of a host to withstand injury by pests; involves a plant response only.

RWA. Russian wheat aphid, *Diuraphis noxia* (Mordvilko).

CP. Mallow's test of independent predictors in regression analysis.

ADH0. Accumulated degree hours < 0°C, used in Chapter 2 regression analysis.

ADH20. Accumulated degree hours > 20°C, used in Chapter 2 regression analysis.

AH0. Accumulated hours with an average temperature < 0°C, used in Chapter 2 regression analysis.

AH20. Accumulated hours with an average temperature > 20°C, used in Chapter 2 regression analysis.

NE. Natural enemies including parasitoids and predators , used in Chapter 2 regression analysis.

ADSC. Average daily snow cover (cm), used in Chapter 2 regression analysis.

ADRF. Average daily rain fall (ml), used in Chapter 2 regression analysis.

Appendix A

SAS programs for Chapter 1 data.

```
Title "RWA-1996-98-99 data analysis with transformed data ";
dm'log;clear;output;clear;'; *( To clean the long and out put screen);
options ls=80 ps=40; *(Output size adjustments);
data rwa96;
infile'c:\myfiles\hassan\54 experiment-96\rwa96-m.txt';
input month 1-2 date 4-5 year 7-8 plot  trt  variety $  first  sndthrd fourth adult mimi;
if plot >= 801 and plot <= 803 then blk=1;
if plot >= 701 and plot <= 703 then blk=1;
if plot >= 601 and plot <= 603 then blk=1;
if plot >= 501 and plot <= 503 then blk=1;
if plot >= 401 and plot <= 403 then blk=1;
if plot >= 301 and plot <= 303 then blk=1;
if plot >= 201 and plot <= 203 then blk=1;
if plot >= 101 and plot <= 103 then blk=1;
if plot >= 804 and plot <= 806 then blk=2;
if plot >= 704 and plot <= 706 then blk=2;
if plot >= 604 and plot <= 606 then blk=2;
if plot >= 504 and plot <= 506 then blk=2;
if plot >= 404 and plot <= 406 then blk=2;
if plot >= 304 and plot <= 306 then blk=2;
if plot >= 204 and plot <= 206 then blk=2;
if plot >= 104 and plot <= 106 then blk=2;
if plot >= 807 and plot <= 809 then blk=3;
if plot >= 707 and plot <= 709 then blk=3;
if plot >= 607 and plot <= 609 then blk=3;
if plot >= 507 and plot <= 509 then blk=3;
if plot >= 407 and plot <= 409 then blk=3;
if plot >= 307 and plot <= 309 then blk=3;
if plot >= 207 and plot <= 209 then blk=3;
if plot >= 107 and plot <= 109 then blk=3;
if plot >= 810 and plot <= 812 then blk=4;
if plot >= 710 and plot <= 712 then blk=4;
if plot >= 610 and plot <= 612 then blk=4;
if plot >= 510 and plot <= 512 then blk=4;
if plot >= 410 and plot <= 412 then blk=4;
if plot >= 310 and plot <= 312 then blk=4;
if plot >= 210 and plot <= 212 then blk=4;
if plot >= 110 and plot <= 112 then blk=4;
if plot >= 813 and plot <= 815 then blk=5;
if plot >= 713 and plot <= 715 then blk=5;
if plot >= 613 and plot <= 615 then blk=5;
if plot >= 513 and plot <= 515 then blk=5;
if plot >= 413 and plot <= 415 then blk=5;
if plot >= 313 and plot <= 315 then blk=5;
if plot >= 213 and plot <= 215 then blk=5;
if plot >= 113 and plot <= 115 then blk=5;
if plot >= 816 and plot <= 818 then blk=6;
if plot >= 716 and plot <= 718 then blk=6;
if plot >= 616 and plot <= 618 then blk=6;
if plot >= 516 and plot <= 518 then blk=6;
if plot >= 416 and plot <= 418 then blk=6;
if plot >= 316 and plot <= 318 then blk=6;
if plot >= 216 and plot <= 218 then blk=6;
if plot >= 116 and plot <= 118 then blk=6;

*(To read the 1-2 cloum as month and so on. $ to distinguish non numerical data so it
comes after the variable (variety);
*and the rest are numerical so no need for $ signe);

firstl= first/(36);
sndthrdl= sndthrd/(36);
fourthl = fourth/(36);
adultl = adult/(36);
mimil = mimi/(36);
RWA = firstl+sndthrdl+fourthl+adultl+mimil;

lg_first=log(firstl+0.375);*(Transformation by log of the dependent variables and because
we have a 0;
lg_sthrd=log(sndthrdl + 0.375); * we have to add a positive number so that the log
function will be defined);
lg_foth=log(fourthl + 0.375);
lg_adult=log(adultl + 0.375);
lg_mimi=log(mimil+0.375);
```

```
lg_RWA=log(rwa+0.375);
*proc sort;*by date;

proc means mean stderr;
  class variety month date ;
  var firstl sndthrdl fourthl adultl;
*(model statment is dependent = independent variables and all other interactions);
run;
/*
proc glm;
class variety trt;*(To deal with the data as sepreat classes);
model lg_rwa = blk variety trt variety*trt;
means variety / snk;*(to test the diffrence among the different variety using lsd tukey
duncan;

contrast 'Dn4 vs Dn6' variety 1 -1 0;
contrast 'Dn4 and Dn6 vs TAM' variety 1 1 -2;
*proc print data=rwa96; *(To print the original data);
 * **************** all dependent variables*********; *(Running glm using the dependent
variabels);
/*proc glm;
*by date;
class blk variety date trt;*(To deal with the data as sepreat classes);
model lg_first lg_sthrd lg_foth lg_adult lg_mimi = blk variety date trt variety*trt;
*(model statment is dependent = independent variables and all other interactions);
means variety / snk;*(to test the diffrence among the different variety using lsd tukey
duncan)
contrast 'Dn4 vs Dn6' variety 1 -1 0;
contrast 'Dn4 and Dn6 vs TAM' variety 1 1 -2;

* *********************** first as dependent *********;
/*proc glm;
*by trt;
*by date;
*by variety;
class  date  variety trt;
 model lg_first  =  variety trt trt*variety/;
output out=stat2 p=pred2 r=resd2;
means variety / snk;
proc rank data=stat2 normal=blom; *(for normal probability plots ofthe residuales);
 var resd2;
 ranks nresd2;
proc gplot;
symbol1 V=star I=none;
symbol2 V=none I=join;
plot resd2*nresd2=1;
plot resd2*pred2=2; *( predicted values vs residuals);
*/
/* *********************** sndthird as dependent *********;
*proc glm;
*class blk month variety trt;
 *model lg_sthrd = blk month variety trt trt*variety trt*month month*variety;
*output out=stat3 p=pred3 r=resd3;
*means variety / lsd tukey duncan;
*proc rank data=stat3 normal=blom;
 *var resd3;
 *ranks nresd3;
*proc plot;
*plot resd3*nresd3='*';


* *********************** fourth as dependent *********;
*proc glm;
*class blk month variety trt;
 *model lg_foth  = blk month variety trt trt*variety trt*month month*variety;
*output out=stat4 p=pred4 r=resd4;
*means variety / lsd tukey duncan;
*proc rank data=stat4 normal=blom;
 *var resd4;
 *ranks nresd4;
*proc plot;
*plot resd4*nresd4='*';
```

```
* *********************** adult as dependent *********;
*proc glm;
*class blk month variety trt;
 *model lg_adult  = blk month variety trt trt*variety trt*month month*variety;
*output out=stat5 p=pred5 r=resd5;
*means variety / lsd tukey duncan;
*proc rank data=stat5 normal=blom;
 *var resd5;
 *ranks nresd5;
*proc plot;
*plot resd5*nresd5='*';


* *********************** mimi as dependent *********;
*proc glm;
*class blk month variety trt;
 *model lg_mimi  = blk month variety trt trt*variety trt*month month*variety;
*output out=stat6 p=pred6 r=resd6;
*means variety / lsd tukey duncan;
*proc rank data=stat6 normal=blom;
 *var resd6;
 *ranks nresd6;
*proc plot;
*plot resd6*nresd6='*';
*/
run;
quit;
```

Proprtion analysis.

```
dm'log;clear;output;clear;'; *( To clean the long and out put screen);
options ls=100 ps=40; *(Output size adjustments);
Data ProprR96 (drop=year);
infile'd:\myfiles\hassan\54 experiment-96\rwa96-m.txt';
input month 1-2 date 4-5 year 7-8 plot trt vty $ first sndthrd fourth adult mimi;
if plot >= 801 and plot <= 803 then blk=1;
if plot >= 701 and plot <= 703 then blk=1;
if plot >= 601 and plot <= 603 then blk=1;
if plot >= 501 and plot <= 503 then blk=1;
if plot >= 401 and plot <= 403 then blk=1;
if plot >= 301 and plot <= 303 then blk=1;
if plot >= 201 and plot <= 203 then blk=1;
if plot >= 101 and plot <= 103 then blk=1;
if plot >= 804 and plot <= 806 then blk=2;
if plot >= 704 and plot <= 706 then blk=2;
if plot >= 604 and plot <= 606 then blk=2;
if plot >= 504 and plot <= 506 then blk=2;
if plot >= 404 and plot <= 406 then blk=2;
if plot >= 304 and plot <= 306 then blk=2;
if plot >= 204 and plot <= 206 then blk=2;
if plot >= 104 and plot <= 106 then blk=2;
if plot >= 807 and plot <= 809 then blk=3;
if plot >= 707 and plot <= 709 then blk=3;
if plot >= 607 and plot <= 609 then blk=3;
if plot >= 507 and plot <= 509 then blk=3;
if plot >= 407 and plot <= 409 then blk=3;
if plot >= 307 and plot <= 309 then blk=3;
if plot >= 207 and plot <= 209 then blk=3;
if plot >= 107 and plot <= 109 then blk=3;
if plot >= 810 and plot <= 812 then blk=4;
if plot >= 710 and plot <= 712 then blk=4;
if plot >= 610 and plot <= 612 then blk=4;
if plot >= 510 and plot <= 512 then blk=4;
if plot >= 410 and plot <= 412 then blk=4;
if plot >= 310 and plot <= 312 then blk=4;
if plot >= 210 and plot <= 212 then blk=4;
if plot >= 110 and plot <= 112 then blk=4;
if plot >= 813 and plot <= 815 then blk=5;
if plot >= 713 and plot <= 715 then blk=5;
if plot >= 613 and plot <= 615 then blk=5;
if plot >= 513 and plot <= 515 then blk=5;
if plot >= 413 and plot <= 415 then blk=5;
if plot >= 313 and plot <= 315 then blk=5;
if plot >= 213 and plot <= 215 then blk=5;
if plot >= 113 and plot <= 115 then blk=5;
if plot >= 816 and plot <= 818 then blk=6;
if plot >= 716 and plot <= 718 then blk=6;
if plot >= 616 and plot <= 618 then blk=6;
if plot >= 516 and plot <= 518 then blk=6;
if plot >= 416 and plot <= 418 then blk=6;
if plot >= 316 and plot <= 318 then blk=6;
if plot >= 216 and plot <= 218 then blk=6;
if plot >= 116 and plot <= 118 then blk=6;
*(To read the 1-2 cloum as month and so on. $ to distinguish non numerical data so it
comes after the variable (vty);
*and the rest are numerical so no need for $ signe);
*lg_pro1=log(pro1-0.375);*(Transformation by log of the dependent variables and because we
have a 0;
*lg_pro23=log(pro2_3 + 0.375); * we have to add a positive number so that the log function
will be defined);
*lg_pro4=log(pro4th + 0.375);
*lg_prodt=log(proadult + 0.375);
*lg_promi=log(promimi+0.375);

if month=4 and date=22 then do; time=1; end;
if month=5 then do; time=9+date; end;
if month=6 then do; time=40+date; end;
if month=7 then do; time=70+date; end;

tot = first+sndthrd+fourth+adult;
```

```
if tot=0 then do;
  pro1=0;
  pro2_3=0;
  pro4th=0;
  proadult=0;
  *promimi=0;

end;
else do;
pro1= first/tot;
pro2_3= sndthrd/tot;
pro4th=fourth/tot;
proadult=adult/tot;
*promimi=mimi/tot;
sumpro= pro1+pro2_3+pro4th+proadult;
end;

proc means mean stderr;
 var pro1 pro2_3 pro4th proadult;
 class vty trt;
 *by vty trt;
 *output out=mtrt sum=s1 s2_3 s4 sad stot;
run;
quit;
/*
data mtrt; set mtrt;
pro1=s1/stot;
pro2_3=s2_3/stot;
pro4=s4/stot;
proad=sad/stot;
*promi=smi/stot;
spro=pro1+pro2_3+pro4+proad;
proc print data=mtrt;
title 'Overall proportions by TREATMENT';

proc sort data=proprr96; by vty;
proc means noprint;
 var first sndthrd fourth adult tot;
 by vty;
 output out=mvty sum=s1 s2_3 s4 sad stot;

data mvty; set mvty;
pro1=s1/stot;
pro2_3=s2_3/stot;
pro4=s4/stot;
proad=sad/stot;
*promi=smi/stot;
spro=pro1+pro2_3+pro4+proad;
proc print data=mvty;
title 'Overall proportions by VARIETY';

proc sort data=proprr96; by trt vty;
proc means noprint;
 var first sndthrd fourth adult tot;
 by  trt vty;
 output out=mtwo sum=s1 s2_3 s4 sad stot;

data mtwo; set mtwo;
pro1=s1/stot;
pro2_3=s2_3/stot;
pro4=s4/stot;
proad=sad/stot;
*promi=smi/stot;
spro=pro1+pro2_3+pro4+proad;
proc print data=mtwo;
title 'Overall proportions by TREATMENT & VARIETY';

run;
proc sort data=proprr96; by blk trt vty;
proc means noprint;
 var first sndthrd fourth adult tot;
 by blk trt vty;
```

```
 output out=one sum=s1 s2_3 s4 sad stot;

data new; set one;
pro1=s1/stot;
pro2_3=s2_3/stot;
pro4=s4/stot;
proad=sad/stot;
*promi=smi/stot;
spro=pro1+pro2_3+pro4+proad+promi;

apro1=arsin(sqrt(pro1));
apro2_3=arsin(sqrt(pro2_3));
apro4=arsin(sqrt(pro4));
aproad=arsin(sqrt(proad));
apromi=arsin(sqrt(promi));
proc print;

proc glm data=new;
 class blk trt vty;
 model pro1 = blk trt|vty;
 random blk/test;
 means trt vty/lsd;
 output out=pred r=_resid_ p=_pred_;
 title 'Analysis For 1st';

proc plot;
 plot _resid_*_pred_;
 plot _resid_*trt;
 plot _resid_*vty;
 plot _resid_*blk;

proc univariate normal plot;
 var _resid_;


proc glm data=new;
 class blk trt vty;
 model pro2_3 = blk trt|vty;
 random blk/test;
 means trt vty/lsd;
 output out=pred r=_resid_ p=_pred_;
 title 'Analysis For 2nd-3rd';

proc plot;
 plot _resid_*_pred_;
 plot _resid_*trt;
 plot _resid_*vty;
 plot _resid_*blk;

proc univariate normal plot;
 var _resid_;


proc glm data=new;
 class blk trt vty;
 model pro4 = blk trt|vty;
 random blk/test;
 means trt vty/lsd;
 output out=pred r=_resid_ p=_pred_;
 title 'Analysis For 4th';

proc plot;
 plot _resid_*_pred_;
 plot _resid_*trt;
 plot _resid_*vty;
 plot _resid_*blk;

proc univariate normal plot;
 var _resid_;


proc glm data=new;
 class blk trt vty;
```

```
 model proad = blk trt|vty;
 random blk/test;
 means trt vty/lsd;
 output out=pred r=_resid_ p=_pred_;
 title 'Analysis For Adult';

proc plot;
 plot _resid_*_pred_;
 plot _resid_*trt;
 plot _resid_*vty;
 plot _resid_*blk;

proc univariate normal plot;
 var _resid_;


proc glm data=new;
 class blk trt vty;
 model promi = blk trt|vty;
 random blk/test;
 means trt vty/lsd;
 lsmeans trt*vty/pdiff;
 output out=pred r=_resid_ p=_pred_;
 title 'Analysis For Mimi';

proc plot;
 plot _resid_*_pred_;
 plot _resid_*trt;
 plot _resid_*vty;
 plot _resid_*blk;

proc univariate normal plot;
 var _resid_;
*/
run;
```

Appendix B

SAS programs for all possible models described in Chapter 2

```
Title " Effect of Biotic and abiotic factors on resistant under C1 97-98-99 'Spring';
dm'log;clear;output;clear;';
options ls=100 ps=80;
data cage98;
infile'd:\myfiles\hassan\cage experiment 97-98\C1 res-spring.txt';

data cages99;
infile'd:\myfiles\hassan\cages -99\C1 res-spring.txt';
input Rwa ADH0 AH0 ADSC ADRF NE ;
proc reg;
model RWA= ADH0 AH0 ADRF NE  / selection=rsquare mse cp;
run;

proc reg;
model RWA= ADH0 AH0 ADRF NE   / selection=maxr;
run;

proc reg;
model RWA= ADH0 AH0 ADRF NE / selection= stepwise;
run;
```

Effect of Biotic and abiotic factors on susceptable under C2-3 cages 97-98-99 winter 58

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N = 4 Regression Models for Dependent Variable: RWA

Number in Model	R-square	C(p)	MSE	Variables in Model
1	0.30429161	1.07002	0.00243498	ADH0
1	0.11012861	1.36865	0.00311455	AH0
2	0.34981624	3.00000	0.00455129	ADH0 AH0

Effect of Biotic and abiotic factors on res under C2-3 97-98-99 winter 59

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Maximum R-square Improvement for Dependent Variable RWA

Step 1 Variable ADH0 Entered R-square = 0.30429161 C(p) = 1.07001810

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	1	0.00213004	0.00213004	0.87	0.4484
Error	2	0.00486996	0.00243498		
Total	3	0.00700000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.01876999	0.06996131	0.00017527	0.07	0.8136
ADH0	-0.00069382	0.00074183	0.00213004	0.87	0.4484

Bounds on condition number: 1, 1

The above model is the best 1-variable model found.

Step 2 Variable AH0 Entered R-square = 0.34981624 C(p) = 3.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	2	0.00244871	0.00122436	0.27	0.8063
Error	1	0.00455129	0.00455129		
Total	3	0.00700000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.00728097	0.10504187	0.00002187	0.00	0.9559
ADH0	-0.00108106	0.00178052	0.00167781	0.37	0.6526
AH0	-0.00000527	0.00001991	0.00031867	0.07	0.8353

Bounds on condition number: 3.082107, 12.32843

The above model is the best 2-variable model found.

No further improvement in R-square is possible.
No variable met the 0.1500 significance level for entry into the model.

Effect of Biotic and abiotic factors on resistant under C2-3 97-98-99 winter 61

01:30 Friday, January 28, 2000

N = 4 Regression Models for Dependent Variable: RWA

Number in Model	R-square	C(p)	MSE	Variables in Model
1	0.97422752	1.05752	0.00001546	AHO
1	0.91670000	3.41804	0.00004998	ADHO
2	0.97562930	3.00000	0.00002924	ADHO AHO

Maximum R-square Improvement for Dependent Variable RWA

Step 1   Variable AHO Entered   R-square = 0.97422752   C(p) = 1.05751889

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	1	0.00116907	0.00116907	75.60	0.0130
Error	2	0.00003093	0.00001546		
Total	3	0.00120000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.02814139	0.00415825	0.00070824	45.80	0.0211
AHO	0.00001404	0.00000161	0.00116907	75.60	0.0130

Bounds on condition number: 1, 1

The above model is the best 1-variable model found.

Step 2   Variable ADHO Entered   R-square = 0.97562930   C(p) = 3.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	2	0.00117076	0.00058538	20.02	0.1561
Error	1	0.00002924	0.00002924		
Total	3	0.00120000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.02713655	0.00708911	0.00042852	14.65	0.1627
ADHO	-0.00005540	0.00023101	0.00000168	0.06	0.8501
AHO	0.00001223	0.00000786	0.00007072	2.42	0.3638

Bounds on condition number: 12.54521, 50.18083

The above model is the best 2-variable model found.

No further improvement in R-square is possible.

Stepwise Procedure for Dependent Variable RWA

Step 1   Variable AHO Entered   R-square = 0.97422752   C(p) = 1.05751889

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	1	0.00116907	0.00116907	75.60	0.0130
Error	2	0.00003093	0.00001546		
Total	3	0.00120000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.02814139	0.00415825	0.00070824	45.80	0.0211
AH0	0.00001404	0.00000161	0.00116907	75.60	0.0130

Bounds on condition number: 1, 1

All variables left in the model are significant at the 0.1500 level.
No other variable met the 0.1500 significance level for entry into the model.

Summary of Stepwise Procedure for Dependent Variable RWA

Step	Variable Entered	Variable Removed	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F
1	AH0		1	0.9742	0.9742	1.0575	75.6022	0.0130

Effect of Biotic and abiotic factors on resistant under C1 97-98-99 winter
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N = 4 Regression Models for Dependent Variable: RWA

Number in Model	R-square	C(p)	MSE	Variables in Model
1	0.14720021	1.02598	0.09076988	ADH0
1	0.12460970	1.05316	0.09317435	AH0
2	0.16879463	3.00000	0.17694284	ADH0 AH0

Effect of Biotic and abiotic factors on resistant under C1 97-98-99 winter
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Maximum R-square Improvement for Dependent Variable RWA

Step 1 Variable ADH0 Entered R-square = 0.14720021 C(p) = 1.02597964

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	1	0.03133524	0.03133524	0.35	0.6163
Error	2	0.18153976	0.09076989		
Total	3	0.21287500			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.26836681	0.27351359	0.08738594	0.96	0.4300
ADH0	-0.00115383	0.00196380	0.03133524	0.35	0.6163

Bounds on condition number: 1, 1

The above model is the best 1-variable model found.

Step 2 Variable AH0 Entered R-square = 0.16879463 C(p) = 3.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	2	0.03593216	0.01796608	0.10	0.9117
Error	1	0.17694284	0.17694284		
Total	3	0.21287500			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F

INTERCEP	0.35157766	0.64214397	0.05304088	0.30	0.6811
ADHO	-0.00370839	0.01608432	0.00940587	0.05	0.8557
AHO	-0.00017538	0.00108808	0.00459691	0.03	0.8983

Bounds on condition number: 34.41271, 137.6508

The above model is the best 2-variable model found.

No further improvement in R-square is possible.

Effect of Biotic and abiotic factors on resistant under CI 97-98-99 winter 66

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Stepwise Procedure for Dependent Variable RWA

No variable met the 0.1500 significance level for entry into the model.

Effect of Biotic and abiotic factors on susceptible under CI 97-98-99 winter 67

01:30 Friday, January 28, 2000

N = 4 Regression Models for Dependent Variable: RWA

Number in Model	R-square	C(p)	MSE	Variables in Model
1	0.13772684	1.34758	0.01504667	AHO
1	0.08396629	1.43160	0.01598479	ADHO
2	0.36013209	3.00000	0.02233139	ADHO AHO

Effect of Biotic and abiotic factors on susceptible under CI 97-98-99 winter 68

01:30 Friday, January 28, 2000

Maximum R-square Improvement for Dependent Variable RWA

Step 1 Variable AHO Entered R-square = 0.13772684 C(p) = 1.34757994

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	1	0.00480667	0.00480667	0.32	0.6289
Error	2	0.03009333	0.01504667		
Total	3	0.03490000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.19702083	0.12570964	0.03695961	2.46	0.2576
AHO	-0.00002790	0.00004937	0.00480667	0.32	0.6289

Bounds on condition number: 1, 1

The above model is the best 1-variable model found.

Step 2 Variable ADHO Entered R-square = 0.36013209 C(p) = 3.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	2	0.01256861	0.00628431	0.28	0.7999
Error	1	0.02233139	0.02233139		
Total	3	0.03490000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F

INTERCEP	0.27889996	0.20674131	0.04064042	1.82	0.4061
ADHO	-0.00330241	0.00560148	0.00776194	0.35	0.6609
AHO	-0.00024377	0.00037106	0.00963813	0.43	0.5300

Bounds on condition number: 38.06407, 152.2563

The above model is the best 2-variable model found.

No further improvement in R-square is possible.

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Stepwise Procedure for Dependent Variable RWA

No variable met the 0.1500 significance level for entry into the model.

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N = 5 Regression Models for Dependent Variable: RWA

Number in Model	R-square	C(p)	MSE	Variables in Model
1	0.96990431	.	0.0868951	AHO
1	0.63249328	.	1.0610997	NE
1	0.55771781	.	1.2769984	ADHO
1	0.10187175	.	2.5931597	ADRF
2	0.98435760	.	0.0677463	ADHO AHO
2	0.97532293	.	0.1068753	AHO NE
2	0.97427327	.	0.1114209	AHO ADRF
2	0.64838595	.	1.5228193	ADHO NE
2	0.63545143	.	1.5788380	ADRF NE
2	0.56075932	.	1.9023250	ADHO ADRF
3	0.99732503	.	0.0231703	ADHO AHO ADRF
3	0.98473460	.	0.1322270	ADHO AHO NE
3	0.98046141	.	0.1692410	AHO ADRF NE
3	0.64838914	.	3.0456111	ADHO ADRF NE
4	1.00000000	.	.	ADHO AHO ADRF NE

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Maximum R-square Improvement for Dependent Variable RWA

Step 1 Variable AHO Entered R-square = 0.96990431 C(p) = .

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	1	8.40119477	8.40119477	96.68	0.0022
Error	3	0.26068523	0.08689508		
Total	4	8.66188000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.40186503	0.24840348	0.22742606	2.62	0.2041
AHO	0.00171653	0.00017457	8.40119477	96.68	0.0022

Bounds on condition number: 1, 1

The above model is the best 1-variable model found.

Step 2 Variable ADHO Entered R-square = 0.98435760 C(p) = .

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	2	8.52638737	4.26319368	62.93	0.0156
Error	2	0.13549263	0.06774632		
Total	4	8.66188000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.50384629	0.23180736	0.32005703	4.72	0.1618
ADHO	0.00594801	0.00437548	0.12519260	1.85	0.3070
AHO	0.00152874	0.00020699	3.69550261	54.55	0.0178

Bounds on condition number: 1.803154, 7.212614

The above model is the best 2-variable model found.

Step 3 Variable ADRF Entered R-square = 0.99732503 C(p) = .

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	3	8.63870973	2.87956991	124.28	0.0658
Error	1	0.02317027	0.02317027		
Total	4	8.66188000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.24974390	0.17803765	0.04559291	1.97	0.3943
ADHO	0.00798983	0.00272173	0.19967155	8.62	0.2090
AHO	0.00155261	0.00012153	3.78147980	163.20	0.0497
ADRF	0.18994772	0.08627135	0.11232236	4.85	0.2714

Bounds on condition number: 2.039983, 15.56107

The above model is the best 3-variable model found.

Step 4 Variable NE Entered R-square = 1.00000000 C(p) = .

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	4	8.66188000	2.16547000	.	.
Error	0	0.00000000	.		
Total	4	8.66188000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.26472546	.	0.05086681	.	.
ADHO	0.01103189	.	0.16924095	.	.
AHO	0.00162565	.	3.04561108	.	.
ADRF	0.21386593	.	0.13222705	.	.

NE	-0.03648625	.	0.02317027	.	.

Bounds on condition number: 5.331818, 55.30378

The above model is the best 4-variable model found.

No further improvement in R-square is possible.

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Stepwise Procedure for Dependent Variable RWA

Step 1 Variable AHO Entered R-square = 0.96990431 C(p) = .

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	1	8.40119477	8.40119477	96.68	0.0022
Error	3	0.26068523	0.08689508		
Total	4	8.66188000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.40186503	0.24840348	0.22742606	2.62	0.2041
AHO	0.00171653	0.00017457	8.40119477	96.68	0.0022

Bounds on condition number: 1, 1

All variables left in the model are significant at the 0.1500 level.
No other variable met the 0.1500 significance level for entry into the model.

Summary of Stepwise Procedure for Dependent Variable RWA

Step	Variable Entered	Variable Removed	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F
1	AHO		1	0.9699	0.9699	.	96.6821	0.0022

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N = 5 Regression Models for Dependent Variable: RWA

Number in Model	R-square	C(p)	MSE	Variables in Model
1	0.29910679	.	642.25862	ADHO
1	0.27043126	.	668.53524	AHO
1	0.18380793	.	747.91193	ADRF
1	0.02735960	.	891.27226	NE
2	0.44456199	.	763.45764	ADHO ADRF
2	0.38491557	.	845.44251	AHO ADRF
2	0.37733096	.	855.86766	ADHO NE
2	0.36029244	.	879.28736	AHO NE
2	0.32579669	.	926.70227	ADHO AHO
2	0.19056587	.	1112.57900	ADRF NE
3	0.84596958	.	423.43411	ADHO AHO ADRF
3	0.48471924	.	1416.52180	ADHO ADRF NE
3	0.43375438	.	1556.62570	AHO ADRF NE
3	0.38270507	.	1696.96173	ADHO AHO NE
4	1.00000000	.	.	ADHO AHO ADRF NE

Effect of Biotic and abiotic factors on resistant under C1 97-98-99
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Maximum R-square Improvement for Dependent Variable RWA

Step 1 Variable ADHO Entered R-square = 0.29910679 C(p) = .

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	1	822.25327248	822.25327248	1.28	0.3401
Error	3	1926.77584752	642.25861584		
Total	4	2749.02912000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	45.73920488	21.50815178	2904.56416778	4.52	0.1234
ADHO	-0.30150444	0.26646850	822.25327248	1.28	0.3401

Bounds on condition number: 1, 1

The above model is the best 1-variable model found.

Step 2 Variable ADRF Entered R-square = 0.44456199 C(p) = .

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	2	1222.11384773	611.05692386	0.80	0.5554
Error	2	1526.91527227	763.45763614		
Total	4	2749.02912000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	52.04814023	25.01784177	3304.42342668	4.33	0.1730
ADHO	-0.28264206	0.29169169	716.82050306	0.94	0.4348
ADRF	-2.01828909	2.78882685	399.86057525	0.52	0.5444

Bounds on condition number: 1.008048, 4.032193

The above model is the best 2-variable model found.

Step 3 Variable AHO Entered R-square = 0.84596958 C(p) = .

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	3	2325.59501113	775.19833704	1.83	0.4866
Error	1	423.43410887	423.43410887		
Total	4	2749.02912000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	97.13691610	33.57454776	3544.32973751	8.37	0.2119
ADHO	-3.97503770	2.29756918	1267.45091321	2.99	0.3336
AHO	0.10927818	0.06769302	1103.48116340	2.61	0.3531
ADRF	-5.51342094	3.00020232	1429.97042677	3.38	0.3173

Bounds on condition number: 115.8284, 692.087

The above model is the best 3-variable model found.

Step 4 Variable NE Entered R-square = 1.00000000 C(p) = .

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	4	2749.02912000	687.25728000	.	.
Error	0	0.00000000	.		
Total	4	2749.02912000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	112.12843267	.	3937.69424761	.	.
ADHO	-6.38726338	.	1556.62569846	.	.
AHO	0.18282737	.	1416.52180471	.	.
ADRF	-8.56039329	.	1696.96173384	.	.

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NE	2.40169732	.	423.43410887	.	.

Bounds on condition number: 252.5645, 1985.149

The above model is the best 4-variable model found.

No further improvement in R-square is possible.

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Stepwise Procedure for Dependent Variable RWA

No variable met the 0.1500 significance level for entry into the model.

Appendix C
SAS programs for Chapter 3 data.

Antixenosis Analysis.

```
Title "Catogorization experiment Antixenosis";
dm'log;clear;output;clear;'; *( To clean the long and out put screen);
options ls=100 ps=90; *(Output size adjustments);
data Sep991;
infile'c:\myfiles\hassan\Catogorization experiment\Growth room
experiment\antixenosism.txt';
input plot variety $ RWA ;
Trial=1;
data Sep992;
infile'c:\myfiles\hassan\Catogorization experiment\Growth room
experiment\antixenosis.txt';
input plot variety $ RWA ;
Trial=2;
data Sep99; set Sep991;
proc append base=Sep99 data=Sep992;
data Sep99; set Sep99;
if plot>= 101 and plot <= 109 then blk=1; *(to compine the blocks);
if plot>= 201 and plot <= 209 then blk=2;
if plot>= 301 and plot <= 309 then blk=3;
if plot>= 401 and plot <= 409 then blk=4;
if plot>= 501 and plot <= 509 then blk=5;
if plot>= 601 and plot <= 609 then blk=6;
if plot>= 701 and plot <= 709 then blk=7;
if plot>= 801 and plot <= 809 then blk=8;
if plot>= 901 and plot <= 909 then blk=9;
*proc print data=Sep99; *(To print the original data);
*run;
proc means mean stdrre;
        class variety ;
        var rwa;

proc glm;
class blk variety trial;
model RWA=blk variety trial blk*Variety*trial;
means variety / lsd bon;
lsmeans variety/pdiff cl;
run;
quit;
```

Antibiosis and Tolerance analysis:

```
*lg_Afec=log(Afec+0.375);
*lg_Adrywt=log(Adrywt+0.375);
*lg_Pbio=log(Pbio+0.375);
*lg_Ind1=log(Index1+0.375);
*lg_Ind2=log(Index2+0.375);
*lg_Ind3=log(Index3+0.375);
*lg_Ind4=log(Index4+0.375);
run;
proc glm;
class blk trial variety trt;
model afterhi pdrywt afec rwa adrywt abio pbio index1 index2 index3 index4=blk trial
variety trt trt*variety trial*variety trial*blk
 trial*trt trial*trt*blk;
means trt/lsd bon;
means variety/ lsd bon;

run;

/*
proc glm;
class blk variety  trt trial;
model afterhi =blk trial variety trt trt*variety;
means trt/lsd bon;
means variety/ lsd bon;
run;
proc means mean stdrre;
class variety;
var afterhi;
run;
proc means mean stdrre;
class trt;
var afterhi;
run;

proc glm;
class blk variety  trt;
model Pdrywt=blk variety trt trt*variety;
means trt/ lsd bon;
means variety/ lsd bon;
run;
proc means mean stdrre;
class variety;
var pdrywt;
run;
proc means mean stdrre;
class trt;
var pdrywt;
run;

proc glm;
class blk variety  trt;
model Afec=blk variety trt trt*variety;
means trt/ lsd bon;
means variety/ lsd bon;
output out=pred r=_resid_ p=_pred_;
proc gplot;
 plot _resid_*_pred_;
 plot _resid_*trt;
 plot _resid_*variety;
 plot _resid_*blk;
proc univariate normal plot;
 var _resid_;
run;
proc means mean stdrre;
class variety;
var afec;
run;
proc means mean stdrre;
class trt;
var afec;
run;
```

```
proc glm;
class blk variety trt ;
model RWA=blk variety trt trt*variety;
means trt/ lsd bon;
means variety/ lsd bon;
proc means mean stdrre;
class variety;
var rwa;
run;
proc means mean stdrre;
class trt;
var rwa;
run;

proc glm;
class blk variety trt;
model Adrywt=blk variety trt trt*variety;
means trt/ lsd bon;
means variety/ lsd bon;
run;
proc means mean stdrre;
class variety;
var adrywt;
run;
proc means mean stdrre;
class trt;
var adrywt;
run;

proc glm;
class blk variety  trt;
model Abio=blk variety trt trt*variety;
means trt/ lsd bon;
means variety/ lsd bon;
output out=pred r=_resid_ p=_pred_;
proc gplot;
 plot _resid_*_pred_;
 plot _resid_*trt;
 plot _resid_*variety;
 plot _resid_*blk;
proc univariate normal plot;
 var _resid_;
run;
proc means mean stdrre;
class variety;
var abio;
run;
proc means mean stdrre;
class trt;
var abio;
run;

proc glm;
where trt ne 0;
class blk variety  trt;
model Pbio=blk variety trt trt*variety;
means trt/ lsd bon;
means variety/ lsd bon;
run;
proc means mean stdrre;
class variety;
var pbio;
run;
proc means mean stdrre;
class trt;
var pbio;
run;

*Index 1;
proc glm;
where trt ne 0;
class blk trt variety;
model index1=blk trt variety trt*variety;
```

```
lsmeans trt variety trt*variety/pdiff cl;
run;
proc means mean stderr;
class variety;
var index1;
run;
proc means mean stderr;
class trt;
var index1;
run;


proc mixed;
where trt ne 0;
class blk trt variety;
model Index2 Index3 Index4= trt variety trt*variety/ ddfm=satterth;
random blk blk*variety;
lsmeans trt variety trt*variety/pdiff cl;
run;

proc mixed;
where trt ne 0;
class blk trt variety;
model Index2= trt variety trt*variety/ ddfm=satterth;
random blk blk*variety;
lsmeans trt variety trt*variety/pdiff cl;
run;
proc means mean stderr;
class variety;
var index2;

proc mixed;
where trt ne 0;
class blk trt variety;
model Index3= trt variety trt*variety/ ddfm=satterth;
random blk blk*variety;
lsmeans trt variety trt*variety/pdiff cl;
run;
proc means mean stderr;
class variety;
var Index3;
run;

proc mixed;
where trt ne 0;
class blk trt variety;
model Index4= trt variety trt*variety/ ddfm=satterth;
random blk blk*variety;
lsmeans trt variety trt*variety/pdiff cl;
run;
proc means mean stderr;
class variety;
var Index4;
*/
run;
```