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Pest Status and Control of the Russian Wheat Aphid, Diuraphis noxia (Mordvilko) (Homoptera: Aphididae). A Review

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ABSTRACT

Since its detection in Texas in March of 1986, the Russian wheat aphid (RWA) has become a serious pest of small grains in the western states of the U.S. This insect has adapted to diverse environments, infesting cultivated cereals and native and introduced grasses. It is presently distributed through 16 western states, from California to Nebraska, and N. Mexico to Montana. It has also been collected in N. Dakota, and southern British Columbia, Alberta, and Saskatchewan in Canada. This aphid damages their hosts by severely disrupting their water balance. There is concern among researchers and producers that this cereal aphid may spread to and infest small grains east of the Mississippi River.

This bulletin reviews the current pest status of the RWA, including aspects of its taxonomy, biology, and damage both by direct feeding and by transmission of several plant virus disease agents. It also discusses control alternatives, considering biological, chemical, and cultural control practices, and the use of plant resistance relative to this insect. Also, it provides a set of references from all countries where this aphid has been found. These references are categorized in one or more subjects, with author and category indexes, to help locate a particular source of information on this important pest of graminaceous plants.

INTRODUCTION

The Russian wheat aphid (RWA), ***Diuraphis noxia*** (Mordvilko) (Homoptera: Aphididae) was first detected in the United States in March of 1986 (Araya *et al.* 1986, Fereres *et al.* 1986, Valiulis 1986). This aphid is capable of causing serious damage to cereal crops, both by direct feeding (Fouché *et al.* 1984, Kruger & Hewitt 1984, Du Toit 1986) and by transmitting several plant virus disease agents (Burnett *et al.* 1984, Rybicki & von Wechmar 1984, von Wechmar 1984, von Wechmar & Rybicki 1984, Williamson *et al.* 1985, Gilchrist *et al.* 1986a). In 1987 and 1988, the RWA cost small grain producers in western states of the U.S. approximately $53.8 (Morrison *et al.* 1988) and $130.4 million (Brooks et al. 1989; Table 3), respectively.

The rapid dispersal of the RWA since its first detection in Texas makes this insect a major threat to barley (***Hordeum vulgare*** L.) and wheat (***Triticum aestivum*** L.) production in the U.S. and Canada (Kindler & Springer 1989b). This insect is generating great concern among specialists, extension agents, and farmers because of the potential threat to small grain producing regions that are still uninfested (Fereres *et al.* 1986).

MORPHOLOGY AND TAXONOMY

The RWA is a small green aphid (ca. 2 mm long) with an elongated body that can be easily distinguished by a prominent supracaudal process which gives it the appearance of a "double-tail" (Figure 1). It has short antennae and small, globular cornicles (Mier Durante & Nieto Nafría 1974, Araya *et al.* 1986, Stoetzel 1987). The head and thorax are black on winged forms have (Ilharco *et al.* 1982). In the field, the RWA can be confused with the greenbug, ***Schizaphis graminum*** (Rondani), mainly because both species are known to be adapted and survive well in dry areas and occur sympatrically throughout their host range.

Some of the synonyms of the RWA in the literature (Araya *et al.* 1987) are ***Brachycolus noxius*** (Mordvilko), ***Cavahyalopterus graminarium*** (Mimeur), ***Cavahyalopterus noxius*** (Mordvilko), and ***Cuernavaca noxia*** (Mordvilko).

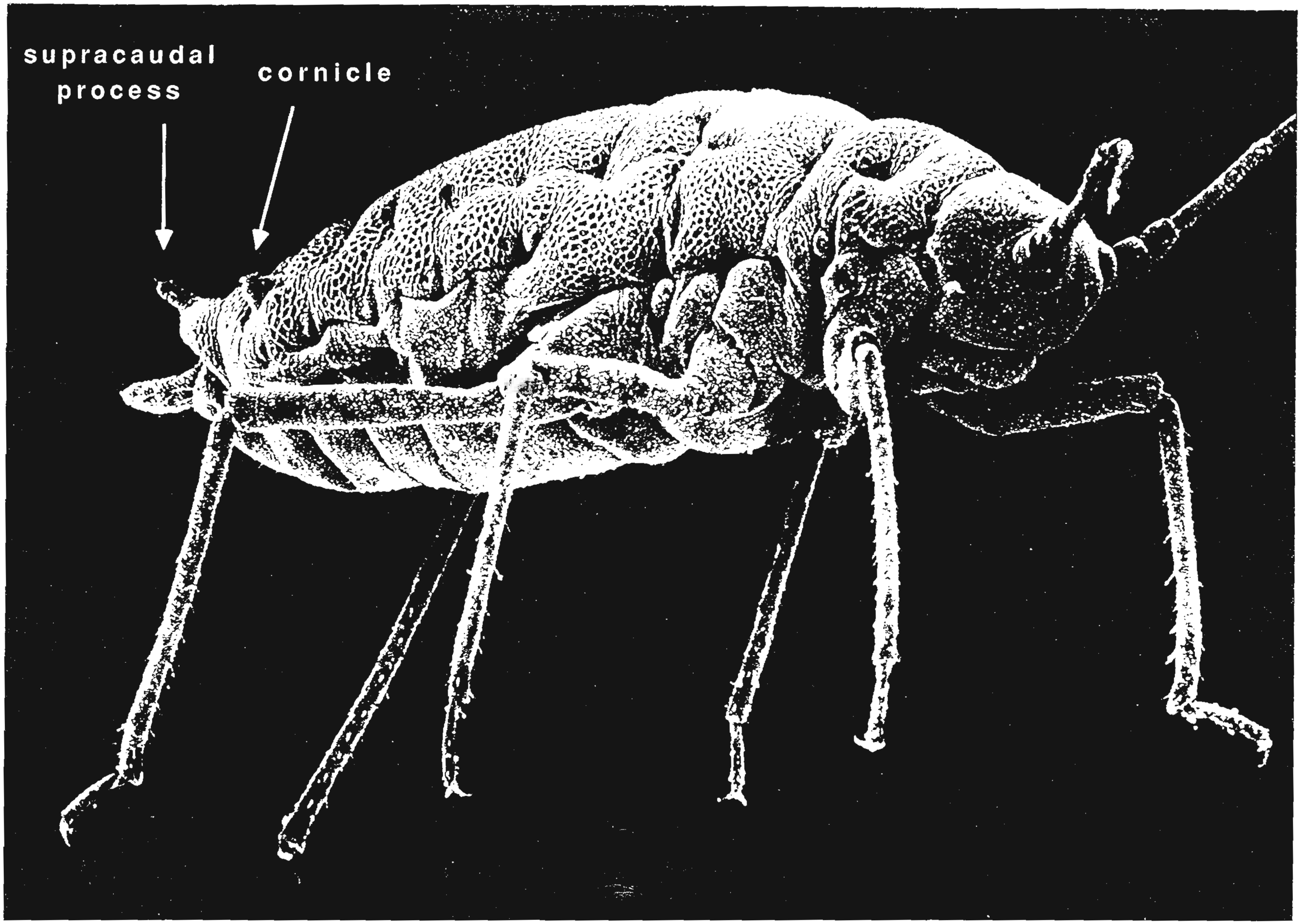

Figure 1. Scanning electron micrograph of an apterous Russian wheat aphid showing the globular cornicle, and supracaudal process or double-tail (taken by N. Bradley, USDA-ARS Plant Stress Lab., Beltsville. MD.)

LIFE HISTORY

The preferred feeding site of the RWA is the new growth and leaf bases of the plant host. Aphids when feeding curl the leaves (Stary & Erdelen 1982), forming a type of protected micro environment inside which the insects live (Erdelen 1981). These insects may also be found in the heads under the glumes living directly on the forming grains (Alfaro 1947). These protected habitats enable the RWA to survive and reproduce under dry conditions, similarly to the corn leaf aphid, ***Rhopalosiphum maidis*** (Fitch). The RWA can survive in extremely arid conditions such as in many localities of the Yemen Arab Republic, where daytime relative humidity is below 20% (Stary & Erdelen 1982). As plants mature, the RWA moves upwards, eventually colonizing the upper leaves (Kriel *et al.* 1984).

The development of winged females depends on the prevailing environmental conditions and the physiological condition of the host plant. Alates are produced under adverse environments and when the quality of the food for aphid development deteriorates (Walters *et al.* 1984). Data from central Spain indicate that the RWA is abundant on wheat only in very dry years (Castañera & Gutiérrez 1985). In the U.S., the RWA oversummers in most of the wheat growing areas where it has been detected, living on native and introduced grasses and volunteer wheat plants as alternate hosts (Kindler & Springer 1989a, 1989b).

According to Michels & Behle (1989), the greatest reproductive rate of the RWA on wheat in the laboratory occurred at 5-15°C. At 1-19°C, the intrinsic rates of increase (r_m) for ***D. noxia, S. graminum***, and ***R. padi*** were 0.188, 0.144, and 0.200, respectively.

An important consideration is the overwintering survival of the RWA in the U.S. Preliminary studies in central Spain indicate that this insect can survive winter temperatures down to -10°C (A. Fereres, unpublished data), thus the RWA may be able to overwinter in most of the U.S. Recently, Butts & Thomas (1989) reported that adult RWA survived temperatures as low as -24.9°C in Lethbridge, Alberta. According to Hammon and Judson (1989), the RWA can survive winter in Colorado on plant hosts on south facing slopes (e.g. irrigation ditches), or rows in field crops. Also, the percentage of infested tillers was greater in E—W than N—S aligned rows.

DISTRIBUTION

a. Center of Origin

The RWA is indigenous to southern Russia, where it has been regarded as a pest of wheat and barley since 1900 (Walters 1984). This insect is capable of traveling many miles by using air currents (Walters *et al.* 1984).

b. World Distribution

The distribution of the RWA includes southern Russia, Turkey, Iran, Afghanistan, Pakistan, the countries bordering the Mediterranean Sea (Blackman *et al.* 1990) and Ethiopia (Haile & Tadesse 1988). According to Stary & Erdelen (1982), this aphid is the most important pest of sorghum and small grains in the Yemen Arab Republic. The RWA was observed in 1945 causing damage in wheat and barley fields in Spain (Alfaro 1947). In 1989, the RWA was collected in Yugoslavia (Anonymous 1990). The RWA has not been reported from Australia or New Zealand (Johnstone *et al.* 1990). This insect was recorded in 1978 as a pest in South Africa (Walters *et al.* 1980), and positively identified in Mexico in 1981 (Gilchrist *et al.* 1984). The RWA has also been found in central Chile (Zerené *et al.* 1988) and there is a reference citing it in Argentina (Blackman *et al.* 1990), although we have been unable to confirm this last report. In Canada, the RWA was reported in 1989 in the provinces of Alberta, British Columbia, and Saskatchewan (Brooks *et al.* 1989). Surveys on Nov. 27, 1989, detected 10-20% RWA infestation levels in more than 80 wheat fields in southern Alberta. Field populations in nearby Montana ranged from 39 to 97% infestation (Anonymous 1990).

c. Distribution in the United States

Apparently the RWA entered Texas or New Mexico from Mexico. The strong prevailing winds may have enabled winged aphids to cross the desert of northern Mexico. The RWA was first detected in the Muleshoe area of Bailey Co., Texas, in late March, 1986 (Valiulis 1986), but it was probably present earlier, since its detection in other areas occurred too rapidly. The RWA may have been undetected earlier because of its resemblance to the greenbug and western wheat aphid, ***Diuraphis tritici*** (Gillette), its relative small size and cryptic coloration, and because of its protected feeding site inside leaf whorls.

By May 1988, RWAs were reported in Arizona, California, Colorado, Idaho, Kansas, Nebraska, New Mexico, Montana, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming (Kindler & Springer 1989b). The RWA is now widely distributed in 16 western states, with a suction trap detection in South Dakota (J. Webster, personal communication) (Figure 2), and has been reported in several southern localities of three Canadian Provinces, (British Columbia, Alberta, and Saskatchewan) (Brooks *et al.* 1989, Butts & Thomas 1989, Wingfield 1989, Anonymous 1990). It is peculiar that the RWA became distributed so rapidly throughout almost all of the western wheat growing areas of the United States, since its first detection in March of 1986. Dispersal of the RWA to eastern states may be hampered by heavy rain, or higher daily relative humidities; however, they will probably continue to move north and east. RWAs have a much higher tolerance to cold than do greenbugs (Harvey & Martin 1988). It is difficult to predict the future distribution of the RWA in North and South America. In Chile, the RWA spread 500 miles southward in one year (M. Gerding, personal communication).

In the U.S., a regional system of insect suction traps is used to monitor cereal aphids and other economically important aphids in eight western states, and has facilitated tracking the dispersion of the RWA (Pike *et al.* 1990).

DAMAGE AND ECONOMIC IMPORTANCE

a. Direct Damage

Wheat and barley are the major hosts of the RWA in the U.S., although it also damages oats (***Avena sativa*** L.), rye (***Secale cereale*** L.), triticale (***Triticosecale*** Wittmack), and sorghum (***Sorghum bicolor*** (L.) Moench) [1] (Brooks *et al.* 1989).

1 Sorghum is a secondary plant host, according to James Webster, USDA-ARS, Stillwater, OK.

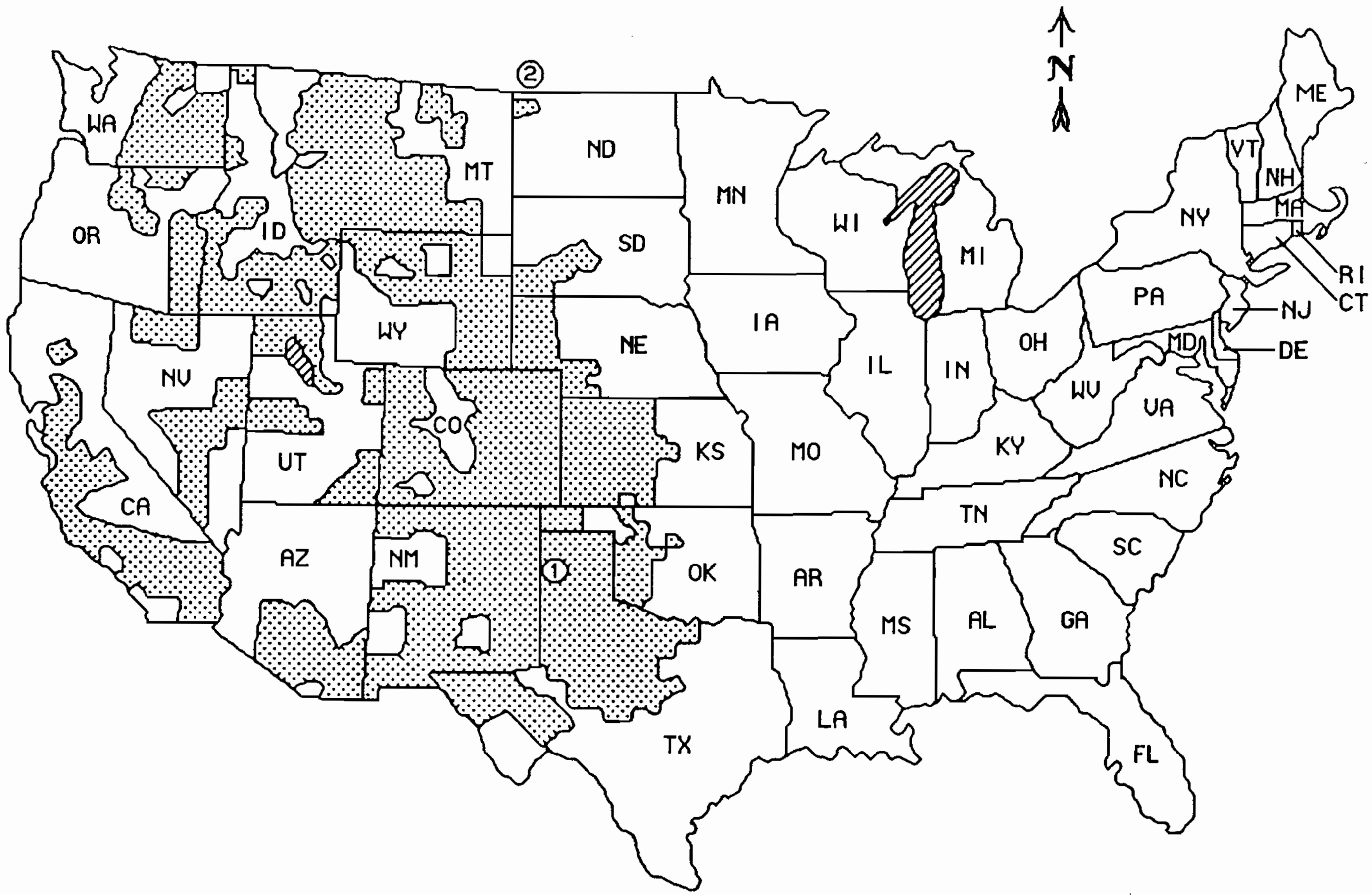

Figure 2. Distribution of the Russian wheat aphid in the United States (1986 - 1990); from map drawn by D. Cooksey, Montana Coop. Agric. Pest Survey Coordinator, in Russian Wheat Aphid News, Vol. 4, № 1 (Feb. 1990). 1: Muleshoe, Bailey Co., initial detection point; 2: only two aphids caught with a suction trap, thus APHIS does not consider N. Dakota infested (J. Webster, personal communication).

Using electronic probing monitoring and histological observations, the RWA was found to be a phloem feeder (Girma and Wilde 1989). On sorghum, the RWA had more initial number of probes, longer salivation, and shorter phloem ingestion than on wheat, oats and rye.

RWA feeding on wheat plants causes longitudinal chlorotic (white, yellow and purple) streaks as well as a convolute curling of the leaf that may result in severely reduced yields (Alfaro 1947, Stary & Erdelen 1982, Walters *et al.* 1980, Pakendorf 1984, Du Toit 1986, 1990, Smith & Schotzko 1989). Initially these symptoms were called "Free State streak disease" in South Africa (Du Toit 1990). The RWA also decreases winter wheat cold tolerance and flag leaf size, kernels per head, and head length (Butts & Thomas 1989, Hein 1989). Other less common symptoms include prostrate tillers, and trapped awns which cause distorted spikes (Figure 3) (Brooks *et al.* 1989). According to Butts and Thomas (1989), fall infestations of RWA reduce wheat yield only when stand reductions occur over the winter. Additionally, the RWA significantly reduces root length, as observed by Gellner *et al.* (1989) in seedlings of 'Rose' hard red winter wheat using a slant-board-absorbent culture technique.

Hewitt *et al.* (1984), Walters *et al.* (1984), and Kriel *et al.* (1986), suggested that damage is caused by a toxin injected during feeding. This toxin degrades chloroplast membranes and decreases the *in vitro* photosynthetic rate (Fouché *et al.* 1984).

Using greenhouse-cultured wheat, triticale, and oat seedlings, Burd *et al.* (1989a, 1989b) evaluated several plant parameters as markers of RWA feeding damage. Results showed that RWA feeding caused significant reductions in both root and shoot biomass, tiller development and leaf initiation were delayed, and significant differences in relative growth rates occurred within 1 week following infestation. However, 1 wk after aphid removal, growth rates resumed to a level equivalent to the controls. This is in sharp contrast to the toxigenic damage caused by the greenbug, where after aphid removal, growth rates increase, although at a decreasing rate relative to the controls Following aphid removal, light microscopy revealed no apparent damage to the vascular bundles or leaf primordia. Epidermal cells of expanded and non-expanded leaves had collapsed, suggesting water imbalances related with reduced turgor. RWA caused a substantial decrease of turgor, with a significant correlation between turgor and damage.

Figure 3. RWA feeding causes a characteristic convolute curling of wheat leaves that trap the awns and bend the heads.

The influence of RWA infestation on the response of cv. 'Hazen' barley plants to drought stress was investigated by Riedell (1989). He infested four ten-day-old seedlings with eight apterous adult RWA for seven days. Leaves previously infested had lower relative water content, reduced stomatal conductance, more negative water potential, low levels of chlorophyll and higher levels of amino-N, proline and glycinebetaine than corresponding leaves from uninfested plants. When water was withheld for seven days after aphids were removed, the relative water content of previously RWA-infested plants dropped steadily from 0.89 to 0.60, while the relative water content of uninfested plants remained at about 0.94 for the first 4 d of the drought stress period, followed by a steady drop to about 0.77 by the end of the drought stress period. Leaf water potentials dropped steadily during the drought stress period in both previously infested (-1.14 to -1.91 MPA) and uninfested (-0.54 to -1.52 MPA) plants. Analysis of glycinebetaine and proline levels at the end of the drought stress period indicated that leaves of previously infested plants accumulated lower levels of these solutes than leaves from uninfested plants. Upon alleviation of the drought stress, plants previously infested with RWA showed little increase in dry weight, while younger leaves and tillers from uninfested plants showed large increases. Riedell (1989) concluded that RWA infestation causes drought-stress symptoms in the leaves of the affected plants even in the presence of adequate root moisture. The low levels of glycinebetaine and proline in the leaves after water was wihheld from the roots, and the lack of leaf growth upon alleviation of drought stress in previously infested plants suggest that RWA infestation limits the capacity of barley to adjust successfully to drougth stress.

Under field conditions in South Africa, the RWA causes yield losses of 35 to 60% in winter wheat (Du Toit & Walters 1984). According to Hewitt (1989), yield losses in wheat in untreated and insecticide-treated tests in 1988 averaged over 50% in South Africa. In Ethiopia, Haile & Tadesse (1988) reported 41-79% barley grain yield losses caused by the RWA. In the U.S., Archer & Bynum (1989b) found approximately a 0.5% yield loss for each 1% infested tiller during the spring preheading growth stages.

In 1988, the Russian Wheat Aphid Investigative Committee of the Crops and Soils Subcommittee of the U.S. Great Plains Agricultural Council estimated that in 1987, the economic impact of this newly introduced pest on producers in the affected states was approximately $ 53,000,000 (Morrison *et al.* 1988).

In 1988, 2.3 million acres were treated with insecticides to control the RWA, at a cost of $17.1 million. The total losses from RWA in the US in 1988 were estimated at $130.4 million (Table 3; Brooks *et al.* 1989).

The economic impact of the RWA in the 1987-88 winter grain season in the US, obtained through questionaires sent to the members of the Russian Wheat Aphid Investigative Committee, is presented in Tables 1-3.

There were small grains on 69,035,000 acres in the 16 western states surveyed in 1988 (Table 1). Approximately 80% of this acreage was sown to wheat. Based on the acreages grown in counties reported to be infested, the RWA infested approximately 40.7% of the small grains acreage. North Dakota remained uninfested, while Colorado, Idaho and New Mexico reported RWA in all small grain growing counties.

Table 1. Small grain production and RWA infested acreage in the western US, 1988 (Brooks *et al.* 1989).

States	State acreage (x 1,000) Wheat (all)	Barley	Oats	TOTAL	Acres in infested areas (x 1,000)	% Acres infested
Arizona	89	22	0	111	40.5	36.5
California	560	360	365	1,285	5.0	0.4
Colorado	2,654	200	110	2,964	2,964.0	100.0
Idaho	1,210	840	65	2,115	2,115.0	100.0
Kansas	10,200	365	0	10,565	5,500.0	52.1
Montana	5,015	2,400	200	7,615	430.2	5.6
Nebraska	2,300	70	650	3,020	1,326.0	43.9
N. Mexico	660	22	0	682	682.0	100.0
N. Dakota	9,500	2,600	1,100	13,200	0.0	0.0
Oklahoma	7,000	35	160	7,195	4,454.4	61.9
Oregon	800	100	0	900	863.0	95.9
S. Dakota	4,065	2,500	0	6,565	120.9	1.8
Texas	8,100	70	1,000	9,170	6,081.0	66.3
Utah	199	0	0	199	160.3	80.6
Washington	2,100	580	75	2,755	2,712.5	98.5
Wyoming	349	168	92	609	474.9	78.0
TOTAL	54,801	10,332	3,817	68,950	27,929.7	40.5

Table 2. Estimated losses from RWA in the western U.S. attributable to yield reduction in 1988 (Brooks *et al.* 1989) *

States	Losses (US$1,000)	Remarks
Arizona	483.3	Based on a 6% yield reduction and crop values of $91.70/ton for barley and $100.75/ton for wheat.
Colorado	11,250.0	3 million bushels at $3.75.
Idaho	29,742.2	Calculated using 5% yield reduction and $3.75/bushel crop value.
Kansas	0.0	Losses due to RWA not separable from other yield constraints. If 5% and $3.75 had been used, losses would have been $27,843,750.
Montana	2,545.1	Calculated using 5% yield loss, $3.75/wheat bu and $2.90/barley bu.
Nebraska	4,119.5	710,000 wheat bu at $3.75 and 502,400 barley bu at $2.90.
N. Mexico	10,094.6	Calculated using 5% yield reduction for irrigated wheat and barley, 20% for dryland wheat and values of $3.75 for wheat and $2.90 for barley.
Oklahoma	13,797.0	Calculated using 10% losses; $3.75 for wheat (excludes oats, barley).
Oregon	9,389.9	Calculated using 5% yield reduction and $3.75/bushel crop value.
Texas	30,700.0	Calculated (by Dr. Steve Amosson, Ext. Ag. Economist) as $24.0 million crop loss, $3.4 million in reduced test weight, and $3.3 million in lost grazing.
Washington	6.8	Loss estimated at 1% on 4,000 acres, 45 bu/acre and $3.75 crop value.
Wyoming	1,126.1	Calculated using 5% yield reduction and $3.75/bushel crop value.
TOTAL	113,254.5	$141,098,250 if 5% loss estimate for Kansas is included.

* RWA not detected in N. Dakota; losses negligible in California, S. Dakota and Utah.

Table 3. Economic impact of the RWA on small grain production in the western U.S. in 1987 and 1988 (Brooks *et al.* 1989) *

Parameters	1987	1988
Infested acres (x 1,000)	16,481.0	27,929.7
Control costs ($1,000)	17,217.5	17,122.3
Losses from yield reductions ($1,000)	36,652.0	113,254.5
Total losses ($1,000)	53,869.5 *	$130,376.9

* If a 1988 crop value of $3.75 were used, the loss would be $72,195,500.

b. Indirect Damage. The RWA as a Vector of Plant Disease Agents

The RWA has been reported to transmit barley yellow dwarf virus (BYDV) in South Africa (Rybicki & von Wechmar 1982, von Wechmar & Rybicki 1984, Rybicki *et al.* 1990), the major worldwide aphid-borne virus disease of small grains (Burnett *et al.* 1984). Researchers in other countries, however, have not been able to confirm the South African reports (Damsteegt & Gildow 1988).

There is general agreement that the RWA is a vector of other virus agents, such as barley stripe mosaic virus (BSMV), brome mosaic virus (BMV), cucumber mosaic virus (CMV), and ***Rhopalosiphum padi*** virus (RhPV, a virus affecting cereal aphid colonies) (Rybicki & von Wechmar, 1982, von Wechmar 1984, von Wechmar *et al.* 1984, Brooks *et al.* 1989, Damsteegt *et al.* 1989, Damsteegt & Hewings 1990, von Wechmar 1990d).

MANAGEMENT

a. Biological Control

Biological control agents of this pest have been studied by Aalbersberg *et al.* (1984). The parasitoid ***Aphidius colemani*** (***A. platensis*** Brethes; Hymenoptera: Aphidiidae), and the ladybird beetle ***Adonia variegata*** (Goeze) (Coleoptera: Coccinellidae) are the species most important in controlling the RWA in South Africa. RWA parasitized by ***A. colemani***, a species probably of Indian origin (Stary, 1972), die forming characteristic brown mummies from which the adult parasitoids emerge. This parasitoid was accidentally or purposely spread over a wide area including South America, Africa, Israel and Australia. It parasitizes many species of aphids; and therefore, is not dependent on and hence not affected by the population dynamics of just one or a few host species. The analysis of climatic conditions, parasitoid habitats and host range led Stary & Erdelen (1982) to conclude that the Yemen Arab Republic might be a promising place for collection and eventual exportation of ***A. colemani.***

Another parasitoid of the RWA in Spain is ***Diaeretiella rapae*** (Castañera & Santiago, 1983). ***Trioxys lambersi,*** a parasitoid of ***Diuraphis holci*** in Holland, may be a potentially useful biological control agent of the RWA because it enters the rolled-up leaves where the aphids feed (Aalbersberg *et al.* 1984).

Other beneficial insects that may feed on the RWA are the coccinellids, ***Scymnus morelleti,*** (that has been observed occasionally searching for prey within rolled-up aphid-infested wheat leaves), ***Lioadalia flavomaculata, Exochomus concavus,*** and ***Cheilomenes lunata*** (Aalbersberg *et al.* 1984). A possible disadvantageous effect of coccinellid predation was reported by Roitberg & Myers (1978). They suggested that coccinellids searching for prey may actually increase the spread of aphid-borne viruses by dislodging aphids, which may move to other plants and spread plant viruses. Additional research is necessary to determine the roles of natural and imported predators in the regulation of RWA numbers; ways for enhancing predation of this insect could then be proposed (Aalbersberg *et al.* 1984).

An aphid pathogenic fungus, ***Triplosporium fresenii*** (Entomophthoraceae), that tolerates low relative humidity, might also control the RWA in dry areas (Aalbersberg *et al.* 1984). In the US, RWA colonies on irrigated spring winter wheat at or near Parma, Idaho, had individuals killed by the fungi ***Pandora (Erynia) neoaphidis, Conidiobulus spp., Beauveria bassiana*** and ***Verticillium lecanii. P. neoaphidis*** was the predominant species consistently causing epizootics and enzootics in Rose grain aphid [***Metopolophium dirhodum*** (Walker)] and RWA populations (Anonymous 1990). In Yugoslavia, ***P. neoaphidis*** was the dominant mortality factor in 1989, causing up to 55% RWA mortality/leaf sheath. This fungus, and ***Conidiobulus obscurus*** were identified by Goettel *et al.* (1990), as parasitizing RWA in southern Alberta, Canada, in 1989.

Native natural enemies do not seem to play a significant role in regulating RWA populations in the U.S. or South Africa. Researchers from the USDA and other agencies are currently collecting biological control agents of the RWA in European and Middle East countries. These agents are being sent to quarantine facilities in the U.S. After biological and host specificity studies, they will be introduced as control agents of the RWA. Several species of microhymenopterans known to parasitize the RWA have been released in western states. This is a continual process and more beneficial agents for the biological control of the RWA will most likely be imported (Brooks *et al.* 1989).

b. Cultural Control

Volunteer wheat and ***Agrotriticum*** (***Agropyron*** x***Triticum*** spp.) are important alternate hosts in South Africa that allow enough aphids to survive summer and fall to infest the cereal fields in the following season (Hewitt *et al.* 1984). Cultural control measures such as the elimination of volunteer wheat, barley or triticale should also be considered. In South Africa, late planted winter wheat reportedly escapes large infestations (Walters *et al.* 1984). ***Bromus*** spp., including rescue grass (***B. willdenovii*** Kunth), and wild oats (***Avena fatua*** L.) are also suitable alternate summer hosts of RWAs and provide a bridge between seasons.

Crop damage by RWA in the U.S. will depend in part on the role of plant species as alternative aestivating hosts (Kindler & Springer 1989). Webster *et al.* (1987) found that besides living on wheat and barley, RWA damage oats, rye, Kentucky bluegrass (***Poa pratensis*** L.), and perennial ryegrass (***Lolium perenne*** L.). They reported little damage to corn (***Zea mays*** L.), sorghum, pearl millet (***Pennisetum americanum*** (K.) K. Schum), 'Kentucky 31' tall fescue (***Festuca arundinacea*** Schreber), and bermudagrass (***Cynodon dactylon*** (L.) Pers.). However, all these plants except corn, maintained reproducing RWA females and were potential over-summering reservoirs of these aphids between wheat crops. In California, Stern & Summers (1989) found ***Bromus catharticus*** Vahl. to be an over-summering host for the RWA in irrigated alfalfa fields.

It appears that RWA can reproduce on many cool- and warm-season grasses in western states (Table 4; Kindler and Springer 1989). Many of the grass species currently recommended and used in the 10-year Conservation Reserve Program (CRP) offer ideal host habitats for RWA which will constitute reservoirs for this important crop pest. According to Walker and Peairs (1989), grazing effectively reduced RWA numbers in all of several planting dates in Southeast Colorado winter wheat.

c. Chemical Control

The colonization of the flag leaf by the RWA can be inhibited and significant yield losses prevented by applying insecticides to plants having the first node visible (Du Toit & Walters 1984). Furthermore, Du Toit (1986) established a negative and linear relationship between winter wheat yield and field infestation levels of the RWA in South Africa.

An infestation of 5.5% on plants at Feekes growth stage 6.0 (Large 1954), with a yield expectation of 2.5 t/ha, justified a single insecticide spray in South Africa (Du Toit & Walters 1984). Du Toit (1986) calculated an economic threshold of 4-7% infested plants at growth stage 31 of the Zadoks scale (first node visible; Tottman *et al.* 1979), and Economic Injury Levels (EIL) of 14% infested plants at growth stage 59 (plants with the heads completely visible).

Systemic insecticides have been recommended for control of the RWA. Contact insecticides are ineffective due to the insect's habit of secluding itself within the rolled leaves typically associated with RWA damage (Webster 1990).. Mixing contact and systemic insecticides has reportedly resulted in effective control (Botha 1984, Valiulis 1986).

Numerous registered and unregistered insecticides in the U.S. have been tested against the RWA (see Table 4). Materials most commonly used commercially include dimethoate, disulfoton, methyl parathion, and parathion (Pike & Suomi 1988, Brooks *et al.* 1989). Promising unregistered insecticides include chlorpyrifos, phosphamidon, fenvalerate and other pyrethroids (Brooks *et al.* 1989).

An evaluation of systemic insecticides applied in furrow at planting for RWA control on winter wheat by Armstrong *et al.* (1989), showed that carbofuran plus liquid fertilizer was effective against the aphid. Carbofuran was ineffective, however, when applied with dry fertilizer.

Araya *et al.* (1990) studied the insecticide action of slow release granular formulations of carbofuran and disulfoton applied at seeding time against the RWA and other cereal aphids (***M. dirhodum*** and ***R. padi***) on wheat in the laboratory. These formulations consist of a matrix of chemically modified granules of corn starch with low solubility in water to which the active ingredients have been incorporated. Disulfoton in pearl corn starch and carbofuran in corn flour had 70.5 and 32.5 days of residual effect against ***D. noxia***, respectively.

In 1987, 2,264,200 acres os small grains in the U.S. were treated with insecticides for control of the RWA. In 1988, the treated area increased to 2,384,900 acres (Brooks *et al.* 1989; Table 5). Of the states that treated for RWA, only Colorado, Nebraska, Oklahoma and Wyoming treated less in 1988 than in 1987. In Colorado 765,000 fewer acres were treated in 1988 than in 1987. Arizona, Idaho, Montana, Oregon, and Washington had crops treated for the RWA for the first time in 1988.

The Colorado Department of Agriculture provided statistics (Table 6) on insecticide treatment of winter and spring wheat and barley against RWA in 1989, based on 2,139 survey responses (Anonymous 1990).

Table 4. Foliar-applied and systemic insecticides registered for control of aphids on small grains in the U.S. (Halbert et al. 1988) [1]

Insecticides	lb a.i./acre	Restrictions
Foliar-applied		
Di-Syston 8E		
Barley	11	30 days to harvest; do not graze
Wheat	3/4	30 days to harvest; do not graze
Cygon 400		
Wheat only	3/8	14 days before grazing immature plant; to days to harvest
Parathion	1/2	15 days to harvest
Penncap M	1/2	15 days to harvest
Systemics		
Di-Syston		
Barley, dryland	1	At planting; 75 days to graze or cut for forage
Barley irrigated	1	60 days to harvest; 30 days to graze or cut for forage
Wheat dryland	1	At planting; 75 days to graze or cut for forage
Wheat irrigated	1	30 days to harvest; 30 days to graze or green chop
Phorate 20G		
Wheat only (over the plant)	1	70 days to harvest; 30 days to graze or cut for forage

[1] Detailed information can be found in Spackman (1989a).

Table 5. Estimated number of acres treated in the U.S. for RWA control in 1988 (Brooks *et al.* 1989) *

	Acres treated (x 1,000)					
States	One application	Second application	Third application	TOTAL	Cost per acre ($)	Total cost ($ 1,000)
Arizona	23.1	0.0	0.0	23.1	8.17	188.70
California	3.0	0.0	0.0	0.0	8.50	25.50
Colorado	350.0	0.0	0.0	350.0	7.80	2,730.00
Idaho	135.0	21.0	0.0	156.0	11.00	1,717.00
Kansas	260.0	5.0	0.0	265.0	7.42	1,966.30
Montana	60.5	3.0	0.0	63.5	7.75	492.10
Nebraska	9.2	0.5	0.0	9.7	7.73	75.00
N. Mexico	470.5	94.1	0.0	564.6	6.50	3,669.90
N. Dakota	0.0	0.0	0.0	0.0	0.00	0.00
Oklahoma	74.0	9.0	2.0	85.0	6.25	531.20
Oregon	11.7	0.0	0.0	11.7	7.81	91.40
S. Dakota	0.0	0.0	0.0	0.0	0.00	0.00
Texas	770.0	70.0	10.0	850.0	6.50	5,525.00
Utah	0.0	0.0	0.0	0.0	0.00	0.00
Washington	4.0	0.0	0.0	4.0	8.00	32.00
Wyoming	9.3	0.0	0.0	9.3	8.43	78.20
TOTAL	2,180.3	192.6	12.0	2,384.9	7.83 *	17,122.30

* Mean cost/acre where insectides were applied.

Table 6. Estimated infestation and number of acres with winter and spring wheat and barley treated in Colorado in 1989 against the RWA (Anonymous 1990) *

Acres (x 1,000)	Winter wheat	Spring wheat	Barley
Total Acres	2,200	70	160
Acres infested with RWA	1,200	6	81
Acres sprayed at least once	832.5	3.5	64.0
% Total acres with RWA	54.6	8.6	50.6
% Total acres sprayed	9.2	0.5	0.0
% infested acres sprayed	69.4	58.3	79.0

* Colorado Dept. of Agriculture Survey 1989. The average cost/acre was $8.30.

d. Plant Resistance

Soon after the initial detection of the RWA in Texas, plant resistance studies were started in the U.S. (Webster *et al.* 1987). In South Africa, resistance to the RWA was identified in ***Triticum monococcum*** (Einkorn) (Butts & Pakendorf 1984) and amphiploids of ***T. monococcum/T. turgidum*** L. var ***durum*** (du Toit & van Niekerk 1985), but this resistance is difficult to transfer to ***T. aestivum*** (Du Toit 1990). ***T. monococcum*** is immune in the field. No-choice feeding in the greenhouse lead to a reduction in the rate of development and reproduction, thus making this plant an important source of resistance to the RWA (Du Toit & van Niekerk 1985). Routine screening of wheat genotypes from the native countries of ***D. noxia*** identified two ***T. aestivum*** lines, PI 137739 and PI 262660, as resistant to the aphid (Du Toit 1987). Further studies (Du Toit 1989a) indicate that resistance is controlled by single dominant genes, Dn1 and Dn2, for PI 137739 and PI 262660, respectively, and that each gene is independently inherited.

Screening for resistance to the RWA in artificial environments has been difficult because visible damage symptoms can occur independently, and the sequence of damage events is further confounded by apparent environmental interactions. Consequently, traditional screening techniques, which are based on monogenic damage scenarios, have failed to give consistent results. Therefore, studies focusing on the basic nature of RWA damage have been conducted to provide a better understanding of the plant response and to facilitate the development of a more precise damage evaluation system (Burd *et al.* 1989a). Plant damage rating schemes have been widely used to evaluate host plant resistance. Rating scales typically range from 1 (no damage) to 9 (dead plant), with intermediate ratings corresponding to incremental levels of visible symptoms (Table 7).

Table 7. Rating evaluation of plant symptoms to RWA damage (Burd *et al.* 1989a).

Ratings	Description of visible symptom of damages
	a. <u>General damage</u>
1	Plants appear healthy; may have small isolated chlorotic spots.
2	Chlorotic spots become more noticeably.
3	Chlorotic spots become larger; up to 15% of total leaf area.
4	Up to 25% of total leaf area is chlorotic.
5	Chlorotic spots coalesced; up to 40% of leaf area is chlorotic.
6	Up to 55% of leaf area is chlorotic.
7	Up to 75% of leaf area is chlorotic.
8	Extensive chlorosis and necrosis; up to 85% of leaf area is chlorotic.
9	Plant death
	b. <u>Leaf rolling damage</u>
1	No leaf rolling.
2	One or more leaves conduplicate.
3	One or more leaves convolute.
	c. <u>Plant stunting damage</u>
1	Height equal to control.
2	Height less than 100% but greater than 75% of the control.
3	Height less than 75% but greater than 50% of the control.
4	Heigtht less than 50% but greater than 25% of the control.
5	Height less than 25% of the control.

Plant lines previously tested as resistant or susceptible were used by Burd *et al.* (1989a) to compare rating system results with specific plant growth characteristics. Entries evaluated included oat (resistant), triticale (resistant and susceptible), and wheat (resistant and susceptible). In addition to the visible damage rating, plant stunting and leaf rolling ratings were made. Plant components quantitatively measured were tiller and leaf development, total leaf area, and total leaf length. Results of the leaf rolling and 1 to 9 damage ratings were consistent with those obtained from the initial screening tests in greenhouse flats. However, plant ratings for stunting indicated that both oat and resistant wheat entries suffered significant reductions in shoot development. Analysis of plant growth components revealed substantial differences between infested and control plants for all entries except the resistant triticale. Clearly, traditional damage rating schemes were adequate for identifying susceptible entries but performed poorly in measuring intermediate damage. Of the three rating systems used, plant stunting best predicted the quantitative damage responses.

Populations of the RWA can be reared on synthetic diets for as many as six generations (Klingauf & de Coll 1982). Such diets might be useful in future plant resistance studies.

Reproductive capacity of RWA is affected by variety, as reported by Bush *et al.* (1989). These authors indicated that two aphids per plant were the best initial infestation level for evaluating wheat resistance to this insect. Higher levels caused too much damage and masked differences between the wheat varieties. Furthermore, there were significant variations in damage between aphid cultures within and between localities, suggesting that there are important genetic variations within RWA populations. In the study by Bush *et al.* (1989), reproductive capacity of RWA was highest on wheat line TX8V2290-36-1 (TXGH2290). After recommending this line for release, these authors proposed that it be used as a susceptible standard in future host plant resistance studies.

It is interesting to note that the RWA in Mediterranean countries, like Spain, is seldom a serious pest of small grains (Castañera & Gutiérrez, 1985). Some workers suspect that the seriousness of the damage caused by infestations in the US may be due to the development of an aggresive RWA biotype. Genetic variability, as observed by Bush *et al.* (1989), may certainly promote the development of insect biotypes, as it has occurred for other aphids, like the greenbug and corn leaf aphid.

Twenty-one new lines of triticale from CIMMYT in Mexico were screened for resistance to RWA and greenbug biotypes C and E by Frank *et al.* (1989). 'Eronga 83', 'Katze "S"' and 'WOMBATS"S"' showed resistance to all three aphids. 'Hare 212' also exhibited a high degree of resistance to RWA, and may be used in wheat breeding programs in the future to control this aphid.

Butts & Pakendorf (1984b) reported that significantly fewer embryos were found in RWA fed on rye as compared with those fed on wheat. They also found that the embryo counts for RWA on triticale where halfway between those of wheat and rye.

Because the North American RWA population appears to be more of a problem in the semiarid regions, resistance in the triticale crop alone would be valuable in plant resistance studies. Furthermore, resistance to RWA in triticale is significant because it will be eventually transferred to wheat (Webster 1990).

Webster (1990) tested 731 ***Triticale*** lines from the USDA-ARS National Triticale Collection for resistance against the RWA. Initial mass screening tests were done in greenhouse flats in environmental chambers at 21:10°C and 14:10 (L:D) photoperiod. Shortly after emergence, the coleoptiles of the triticale test plants were infested with an undetermined mixture of about 10 nymphs and adult RWA per plant by placing infested leaves from laboratory culture plants on the soil between the test plants in the flat. The plants were observed daily, and about 14-21 d after infestation, those plants that were green were considered resistant and were transplanted into individual pots for seed increase and crosses. Seven triticale lines with varying degrees of resistance were identified. Four lines from Russia (P.I. 386148, P.I. 386149, P.I. 386150, and P.I. 386156) and one from California (C.I. 82) were the most resistant in the screening tests. Additional tests were done with all seven lines to determine the mechanism of resistance. Antibiosis was the most discernible mechanism of resistance, with significantly less reproduction occurring on the triticales than on 'TAM W-101' wheat, or 'Snoopy' rye. Greater levels of resistance in the triticales were observed also in the antixenosis and tolerance tests.

In screening studies for plant resistance to the RWA, Smith & Schotzko (1989) identified 5 wheat accessions without the typical leaf rolling symptom caused by RWA feeding. In their study, 4.2% of 542 accessions tested were resistant to this aphid. Recently, Meyer *et al.* (1989) found T-57 ***T. turcikum*** wheat (PI 372129) to be highly resistant to the RWA. However, this line is very susceptible to lodging and plant disease agents.

Webster *et al.* (1989a) found resistance in several barley (s = spring; w = winter) lines from Afghanistan [P.I. 366444, P.I. 366447, P.I. 366449 (s), P.I. 366450 (s), and P.I. 366453 (s)], Iran [C.I. 1412, P.I. 43140, and P.I. 43142 (w)], and Spain (P.I. 430142). Of these lines, C.I. 366444 from Afghanistan had a noticeably better plant resistance index than the other 523 barley lines tested. The mechanisms of resistance to the RWA in these lines were antibiosis in P.I. 366449 and P.I. 336450, and tolerance in P.I. 366444, P.I. 366450, and C.I. 1412.

Host suitability and harboring of RWA by grain cereals and grasses were evaluated by Kindler & Springer (1989b), who provided the list of species in Table 8. This Table contains valuable information on plant host suitability to the RWA that is applicable to plant resistance studies against this insect.

Table 8. Mean counts of RWAs ± SE on cool-season and warm-season grasses after a 14-d infestation period (Kindler & Springer 1989b) [1]

Scientific names	Common names	Mean counts ± SE
a. Cool-season		
Triticum cylindricum (Host) Ces.	Jointed goatgrass	597.50±42.13
Hordeum vulgare L.	Barley	352.37±52.39
Elymus arenarius L.	European dunegrass	287.75±136.61
Hordeum pusillum Nutt.	Little barley	255.50±19.25
Vulpia myuros (L.) C. Gmelin	Rattail fescue	237.50±109.08
Bromus mollis L.	Blando bromegrass	212.50±27.54
Triticum aestivum L.	Wheat	192.50±41.02
Bromus arvensis L.	Field bromegrass	192.00±41.83
Agropyron intermedium (Host) P. Beauv.	Intermediate wheatgrass	186.00±7.62
Agropyron elongatum (Host) P. Beauv.	Tall wheatgrass	155.75±15.39
Oryzopsis hymenoides (Roemer & Schultes) Ricker	Indian ricegrass	149.25±35.59
Elymus triticoides Buckl.	Beardless wildrye	132.75±27.25
Agropyron trachycaulum (Link) Malte	Slender wheatgrass	124.16±25.35
Agropyron riparium Scrib. & Sm.	Streambank wheatgrass	115.75±65.54
Elymus giganteus Voh	Mammoth wildrye	114.75±21.80
Elymus angustus (Trin.) Pilger	Altai wildrye	102.25±55.79
Agropyron spicatum (Pursh) Scrib. & Sm.	Bluebunch wheatgrass	96.75±16.53
Agropyron repens* x *spicatum	Hybrid wheatgrass	96.37±9.76
Elymus junceus Fischer	Russian wildrye	81.75±65.32
Agropyron dasystachium (Hook.) Scribn.	Thickspike wheatgrass	81.25±47.30
Agropyron cristatum (L.) Gaertner	Crested wheatgrass	73.50±29.97
Festuca rubra L. spp. subra	Red fescue	72.75±19.09
Festuca pratensis Hudson	Meadow fescue	62.25±28.99
Stipa viridula Trin.	Green needlegrass	59.75±43.80
Festuca ovina duriuscula (L.) Koch	Hard fescue	57.75±10.34
Bromus inermis Leysser	Smooth bromegrass	56.75±90.27
Poa ampla Merr.	Big bluegrass	55.75±29.98
Avena sativa L.	Oats	53.50±24.28
Agropyron smithii Rydb.	Western wheatgrass	53.43±9.83
Bromus tectorum L.	Downy bromegrass	46.00±30.04
Alopecurus arundinaceous Poiret	Creeping foxtail	39.41±18.26
Bromus rubens L.	Red bromegrass	38.25±12.71
Lolium perenne L.	Perennial ryegrass	31.80±1.92
Secale cereale L.	Cereal rye	29.87±20.16
Poa arida Vasey	Plains bluegrass	29.75±34.77
Elymus cinereus Scribn. & Merr.	Basin wildrye	27.50±18.66
Koeleria cristata (L.) Pers.	Prairie junegrass	19.25±16.03
Lolium multiflorum Lam.	Annual ryegrass	17.00±3.74
Poa juncifolia Scribn.	Alkali bluegrass	17.00±7.07
Festuca arundinacea Schreber	Tall fescue	12.50±11.82
Dactylis glomerata L.	Orchardgrass	12.29±8.21
Puccinellia airoides (Nutt) S. Watson & Coulter	Nuttall's alkaligrass	5.25±4.99

Table 8. Continued...

Scientific names	Common names	Mean counts ± SE
a. Cool-season		
Poa compressa L.	Canada bluegrass	5.25±2.06
Agropyron trichoporum (Link) Halacsy	Pubescent wheatgrass	4.75±3.10
Agrostis alba L	Redtop	2.75±4.86
Poa pratensis L.	Kentucky bluegrass	0.87±1.18
Phalaris arundinacea L.	Reed canarygrass	0.25±0.50
Oryzopsis coerulescens (Desf.) Hack	Mediterranean ricegrass	0.00
b. Warm-season		
Leptochloa dubia (H.B.K.) Nees.	Green sprangletop	92.75±20.98
Bouteloua gracilis (Willd. ex Kunth) Lagasca ex Griffiths	Blue grama	59.13±21.45
Pennisetum americanum (K.) K. Schum.	Pearl millet	31.21±8.31
Eragrostis tef (Zuccagni) Trotter	Teff	29.25±21.64
Bouteloua curtipendula (MIchaux) Torrey	Side-oats grama	28.68±7.27
Bouteloua erlopoda (Torrey) Torrey	Black grama	27.12±8.39
Buchloë dactyloides (Nutt.) Engelm.	Buffalograss	26.66±16.92
Panicum texanum Buckl.	Texas panicum	22.00±23.64
Eragrostis trichodes (Nutt.) Wood	Sand lovegrass	21.50±19.07
Spartina pectinata Link	Prairie cordgrass	19.75±4.11
Brachiaria platyphylla (Griseb.) Nash	Broadleaf signalgrass	19.50±27.60
Sprobolus airoides (Torrey) Torrey	Alkali sacaton	19.16±9.16
Sorghastrum nutans (L.) Nash	Indiangrass	11.85±13.87
Cynodon dactylon (L.) Pers.	Bermudagrass	11.50±12.77
Eragrostis cuperba	Wilman lovegrass	9.25±2.99
Eragrostis lehmanniana Nees.	Atherstone lovegrass	7.50±10.66
Sporobolus wrightii Munro ex Scribn.	Big sacaton	5.50±3.70
Panlcum virgatum L.	Switchgrass	1.00±1.41
Andropogon gerardi Vitman	Big bluestem	0.00
Bothriochloa caucasica (Trin.) Hubb.	Caucasian bluestem	0.00
Bothriochloa ischaemum (L.) Keng	Yellow bluestem	0.00
Dichantelium clandestinum (L.) Gould	Deertongue	0.00
Dichantium Willemet	Old world bluestem	0.00
Digitaria sanguinalis (L.) Scop.	Crabgrass	0.00
Echinochloa crus-galli (L.) P. Beauv.	Barnyard grass	0.00
Eragrostis curvula (Schrader) Nees.	Weeping lovegrass	0.00
Panicum coloratum L.	Kleingrass	0.00
Panicum dichotomiflorum Michaux	Fall panicum	0.00
Paspalum notatum Fluegge	Pensacola bahiagrass	0.00
Pennisetum orientale (Willd.) L. C. Rich.	Lourisagrass	0.00
Schizachyrium scoparium (Michaux) Nash	Little bluestem	0.00
Setaria glauca (L.) Beauv.	Yellow foxtail	0.00

[1] Individual means of zero were not included in the statistical analysis; means may be compared between parts a and b of the Table; least significant difference ($P<0.05$) = 48.73

CONCLUDING REMARKS

The rapid spread of the RWA into diverse small grain producing regions of the world and its recent introduction and spread in North American countries during the last decade, illustrate the importance of conveying information on insect pest management. We have prepared this manuscript with information coming from diverse sources, and hope the aspects of the biology and control of the RWA herein provided will be of use for extension agents and will assist other researchers in the development of further control strategies through studies of aphid biology, plant resistance, biological, chemical and cultural control methods. A large number of specialists are working in all these control aspects. Since most small grains are not treated with insecticides to control insect pests, it is environmentally very important that other control practices be developed. In the case of the RWA, biological control agents and host plant resistance should be introduced as quickly as possible to ensure lowering the damage caused by this aphid. Still, insecticides have to be studied for their residual action, properties, selectivity and application methods, as they continue to be an important management tool in agriculture when properly applied.

REFERENCES

Research on the Russian wheat aphid in the U.S. has increased rapidly, creating an increasing need of references of literature on this insect. Given this huge increase in research on *D. noxia* in North America since 1987, this bibliography updates that on the same species by Araya *et al.* (1987), and continues the series on other cereal aphids by the same authors [Appendix: bird cherry-oat aphid, *Rhopalosiphum padi* (L.) (Foster *et al.* 1985), English grain aphid, *Macrosiphum (Sitobion) avenae* (F.) (Araya *et al.* 1986), and greenbug, *Schizaphis graminum* (Rondani) (Araya *et al.* 1989)]. It contains all papers that have been available to us. Most of the references have been located in Biological Abstracts, Abstracts of Entomology, and Review of Applied Entomology, Series A (Agricultural). Original articles should be consulted for details. All references have been assigned one or more subject categories, according to the following classification:

B	-	Biology; Life History
BC	-	Biological Control; Predators and Parasitoids
CC	-	Cultural Control
CH	-	Chemical Control
D	-	Damage
G	-	Geographic Distribution; Records
H	-	Host Plants
P	-	Physiology
PR	-	Plant Resistance
S	-	Systematics; Taxonomy; Morphology
T	-	Traps; Sampling; Forecasting
TA	-	Techniques and Apparatus; Models
TD	-	Transmission of disease agents

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Footnotes

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