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Resistance in Barley (*Hordeum vulgare* L.) to New Invasive Aphid, Hedgehog Grain Aphid (*Sipha maydis*, Passerini) (Hemiptera: Aphididae)

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Abstract

Sipha maydis Passerini (Hemiptera: Aphididae) is a pest of cereals in many regions of the world and was identified as an invasive pest of the US in 2007. Regional surveys from 2015-2017 revealed this pest was broadly distributed throughout many of the western Great Plains states where it is a potential threat to cereal production. The common name hedgehog grain aphid, HGA, has been associated with *Sipha maydis* in the US. Cross-resistance where a plant is resistant to one aphid species and is also resistant to another species that is known to occur. Six barleys were evaluated for cross-resistance to HGA: Russian wheat aphid, RWA, resistant germplasms STARS 9301B and STARS 9577B and cultivar "Mesa"; greenbug, GB, resistant germplasm STARS 1501B and cultivar "Post 90"; and RWA and GB resistant experimental line 00BX 11-115. Cultivars "Morex" and "Schuyler" were susceptible controls. Antixenosis was measured 5 days after infestation by HGA. Seedling damage ratings and reductions in seedling growth were recorded after 17 days of infestation. Intrinsic rate of increase, r_m, of HGA was determined by following the development of newborn aphids to adulthood and reproduction. 00BX 11-115 and Post 90 had significantly greater antixenosis (fewer aphids/seedling), significantly lower plant damage ratings, and significantly lower intrinsic rates of increase than other entries. Differences in seedling growth were not significant. 00BX 11-115 and Post 90 were the only entries with the *Rsg*1 greenbug resistance gene. *Rsg*1 greenbug resistance confers cross-resistance to HGA in the seedling stage.

Keywords

Greenbug Resistance, Russian Wheat Aphid Resistance, Aphid Resistance, Antixenosis, Plant Damage Ratings, Hedgehog Grain Aphid

1. Introduction

Sipha maydis Passerini is distributed throughout most cereal producing countries of the world. In Pakistan [1] and Iran [2], *S. maydis* is reported to be among the most common aphid species affecting wheat. *S. maydis* was first reported in Argentina in 2002 followed by spread throughout the country by 2006 where it primarily infested wheat, barley, and wild grasses [3]. By 2007 it was detected in the US infesting giant wild rye, *Leymus condensatus* in CA [4]. Infrequent reports of *S. maydis* on wild grasses and wheat ranged from the SW US to the SE costal states over the next few years. A report of *S. maydis* infesting oats near Albuquerque, NM in 2014 instigated a survey in CO in 2015 where it was found on winter annual grasses at many sites in WC and SW CO [5]. The common name, hedgehog grain aphid, HGA, was suggested for this new invasive pest. HGA has been reported on volunteer wheat in UT. Multi-state surveys from 2015-2017 in the Rocky Mountain and Southern plains states determined HGA was broadly distributed and adapted to a variety of wild grasses, barley, sorghum, and wheat with the greatest concentration in W CO and NW NM [6].

HGA feeding was devastating to mature wheat plants on the prairies of Buenos Aries province in Argentina in 2005 [3]. HGA was found in young leaves in the fall and in the ligula area of flag leaves in the late spring where chlorosis reduced functional leaf area and inhibited head growth. Chlorosis from HGA feeding spread beyond the feeding site indicating HGA is a phytotoxic aphid. HGA is also an efficient vector of the luteovirus barley yellow dwarf (BYDV) a significant disease of wheat and barley [7]. HGA is a dual threat to small grain production.

Barley production in the Great Plains and Rocky Mountain States was valued at $529 million in 2018 [8]. Development of resistant cultivars is the most economically and environmentally sound control method for insect attack. Few studies on resistance to HGA have been reported, and in 2013 leaf pubescence of several wheat genotypes was determined as not an effective for providing resistance against *S. maydis* [9]. However, in 2011 antibiosis was evaluated in 47 commercial wheat cultivars from Argentina and 24% had high levels of antibiosis with both nymphal development and reproduction negatively affected [10]. The vulnerability of US cultivars to HGA has yet to be established. Identification of HGA resistance is inhibited by the physical restraints of quarantine required by APHIS to experiment with HGA in the US. Cross-resistance, where sources resistant to one aphid species is also resistant to another species, has been demonstrated in wheat [11] and sorghum [12]. Identification of cross resistance for HGA in established aphid resistant barley cultivars would present a tremendous opportunity to quickly deploy resistance to HGA. There are 2 greenbug resistance genes, *Rsg*1 and *Rsg*2, and 3 RWA resistance genes, *Rdn*1, *Rdn*2, *and*

*Rdn*3, identified in barley. These genes are available in 5 deployed cultivars where *Rsg*1 = Post 90, *Rsg*2 = STARS 1501B barley, and an experimental barley 00BX 11-115 which includes *Rsg*1 and an unidentified resistant source known as *Rdny* (**Table 1**). The known resistance RWA resistance genes *Rdn*1, *Rdn*2, *and Rdn*3 are in STARS 9301B, while *Rdn*1, *Rdn*2 are also in STARS 9577B. A 6th cultivar cv Mesa has been deployed with a unique, unidentified source of RWA-resistance termed *Rdnx*. (**Table 1**). It is the objective of this study to determine the potential for cross resistance to HGA by measuring antixenosis (plant preference), plant damage, plant growth, and intrinsic rate of increase in cultivars/germplasm previously identified as resistant to GB and RWA.

2. Materials and Methods

HGA used in this study came from a *S. maydis* colony collected near Taos, NM in 2017. They were cultured on aphid susceptible "Yuma" wheat in clear plastic cylinder cages in a room with a temperature of 21˚C and a photoperiod of 14:10 L:D provided by a light rack equipped with eight, fluorescent grow lights (#7866113, Philips Inc., Guadalajara, Mexico).

Aphid-resistant cultivars and germplasm utilized in this study include Post 90, STARS 1501B, STARS 9301B, STARS 9577B, Mesa, and experimental line 00BX 11-115. Resistant genes and other agronomic characteristics for each entry are found in **Table 1**. *Rsg*1 has been deployed in cultivar "Post 90" [13], while *Rsg*2 has been released in germplasm line STARS 1501B [14]. Four Russian wheat aphid-resistant barley cultivars have derived their resistance from 2 germplasm lines STARS 9301B [15] and STARS 9577B [16]. STARS 9301B carries 3 RWA-resistant genes, *Rdn*1, *Rdn*2, *and Rdn*3 [17], while STARS 9577B carries *Rdn*1 and *Rdn*2 [18]. The variety Mesa carries unnamed resistance gene(s) from another source [19]. Experimental line 00BX 11-115 has both *Rsg*1 resistance as well as RWA resistance from a unique source. Cultivars Morex [20] and Schuyler [21] were susceptible controls. Both spring and winter growth habits are represented by the cultivars/germplasm (**Table 1**).

Table 1. Resistance genes, target aphid, growth type and designation of barley entries.

Entry	Resistance gene(s)	Target Aphid	Growth type	Designation
STARS 9301B	*Rdn*1, *Rdn*2, *Rdn*3	RWA	Spring	Germplasm
STARS 9577B	*Rdn*1, *Rdn*2	RWA	Spring	Germplasm
Mesa	*Rdnx**	RWA	Winter	Cultivar
00BX 11-115	*Rsg*1, *Rdny**	GB, RWA	Winter	Experimental Line
Post 90	*Rsg*1	GB	Winter	Cultivar
STARS 1501B	*Rsg*2	GB	Spring	Germplasm
Morex	susceptible		Spring	Cultivar
Schuyler	susceptible		Winter	Cultivar

**Rdnx* and *Rdny* indicate a resistance gene not yet identified.

Plant damage response and aphid preference were measured in a completely randomized design with 10 replications in the fall of 2018. The experiment was conducted in a growth chamber (Conviron®, Winnipeg, Canada) set at 21˚C and 14:10 L:D photoperiod with lighting provided by seven TS 32W Ecolux® daylight fluorescent lamps (Fairfield, Connecticut, USA) and four 60W incandescent bulbs. This model of growth chamber is divided in two identical sections, and within these two were conducted an infested portion where entries were challenged with HGA, while the other compartment grew an identical set of entries that were not infested allowing for comparative plant growth measurements such as numbers of leaves and plant height. Each of the entries were planted 2 seeds to a cell in potting soil (Sun Gro Horticulture, Agawam, MA 01001 U. S.) within 25 cell miniflats (Growers Supply, Dyersville, IA 52042). The Mini-flats measured 18 cm in width × 27 cm in length × 30 cm in depth were then placed in a tray measuring 27 cm wide × 38 cm long × 6 cm high filled with construction grade sand which served as a bed to seal a metal frame cage over each mini-flat. Metal frame cages measuring 30 cm wide × 40 cm long × 30 cm tall and were covered with fine mesh nylon screen. Seven d after planting, the healthiest seedling of the 2 planted was chosen to continue in the experiment, while the other was removed. When seedlings were 4 - 6 cm in height ten d after planting, they were infested with 10 aphids on each entry by transferring them one at a time using a camel-hair brush. A companion set of non-infested controls was planted and kept aphid free in an identical compartment of the growth chamber as described above. Five days after infesting, the number of sugarcane aphids per seedling was counted to determine aphid preference, antixenosis by removing the caged flat from the growth camber and removing the screened framed cage from the tray where each plant was examined non-destructively and HGA counted using a 10x magnifying visor. On the day of the evaluation, 17 d after infesting, and when the susceptible entries were near death, plant damage was assessed using the 1 - 9 rating scale described for RWA in which ratings increase with increasing levels of leaf chlorosis/necrosis (1 = healthy, 2 = 1% - 5% chlorosis, 3 = 5% - 20% chlorosis, 4 = 21% - 35% chlorosis, 5 = 36% - 50% chlorosis, 6 = 51% - 66% chlorosis, 7 = 66% - 80% chlorosis, 8 = 81% - 95% chlorosis, and, 9 = dead; [22]. The number true leaves were counted excluding the cotyledon leaf and plant height was taken using a metric ruler where plant height for each entry and replication were measured from the soil surface to the most distal portion of the top leaf. Differences in the number of true leaves and plant height within an entry were made by subtracting each replication of the infested entries from the non-infested replicates.

Intrinsic rate of increase parameters was measured in the same growth chamber described above with a temperature of 22˚C and a 14:10 L:D photoperiod. Two seeds of each barley entry were planted into potting mix described above within a 7.5 cm plastic pot. Each individual pot was covered with a 5 cm diameter × 41 cm plastic tube cage and pots placed in the growth chamber. When seedlings reached the 2-leaf stage they were infested by a single viviparous female which was removed after 24 h. From these nymphs on each entry, a single, 24 hold, nymph per seedling was selected to remain on the plant where the development time to reproductive adult (d) and reproduction (Md) was recorded. Intrisic rate of increase (rm) was calculated using the formula: r_m = 0.0738 $(1ogeM_d)/d$ [23].

Data on antixenosis, reduction in plant height and leaf number were analyzed using PROC MIXED [24] where mean comparisons were made by using the Least Significant Differences Method (LSD) at P > ltl ≤ 0.05 level [24]. Plant damage ratings for barley entries were compared by nonparametric analysis (NPAR1WAY) using Wilcoxon tests to conduct pair-wise comparisons among all entries to establish significant differences at $P > X^2 \leq 0.05$. Aphid antixenosis and plant growth factors were correlated to leaf damage using Pearson's correlation coefficients (Prob > lrl under H0: Rho = 0) using PROC CORR [24].

3. Results

There were varying degrees of damage caused by HGA feeding on the 6 barley genotypes that had previously been proven resistant to either GB or RWA, and the 2 known sources that were used as susceptibles in the evaluation (**Figure 1**) The entries barley 00BX 11-115 and Post 90 had significantly fewer aphid numbers per seedling (**Table 2**) than any other entry showing non-preference (high antixenosis) by HGA compared to all other entries. Morex and STARS 9301B had aphid numbers significantly greater than all other entries indicating low antixenosis for HGA. All other entries had intermediate aphid numbers/seedling. Antixenosis was only moderately correlated with seedling damage ratings (r = 0.42. P = 0.0001; n = 80).

00BX 11-115 and Post 90 had significantly lower plant damage ratings than all other entries (**Table 2**). Their low damage ratings indicate a high level of resistance in these lines. All other entries had a moderately susceptible to susceptible level of resistance to HGA.

HGA infestation reduced seedling height on all barley entries by 47.9% - 61.9% in comparison to non-infested controls. 00BX 11-115 had the least reduction but was not significantly different than reductions for Post 90, STARS 1501B and Morex. There was a poor relationship between plant damage rating and percent reduction in seedling height (r = 0.24. P = 0.03; n = 80).

Percent reduction in leaf number of entries for infested seedlings compared to non-infested controls ranged from 26.7% - 33.3% and was not significant (**Table 2**). There was no significant relationship between percent leaf number reduction and plant damage ratings (r = 0.18. P = 0.10; n = 80) or between percent leaf number reduction and percent seedling height reduction (r = 0.12. P = 0.29; n = 80).

Days to reproductive adult, fecundity rate, and intrinsic rates of increase were significantly affected by barley entry (**Table 3**). HGA feeding on Post 90 had the greatest number of days from newborn nymph to reproductive adult and was significantly greater than all lines but 00BX 11-115 and STARS 9301B. 00BX 11-115 had significantly greater number of days to reproduction than all lines except Post 90, STARS 9301B, and Schuyler. The number of days to reproduction of HGA feeding on STARS 9301B was significantly greater than the number of days for remaining lines except Schuyler. Fecundity rate was significantly lower for 00BX 11-115 and Post 90 than all other entries. Intrinsic rate of increase was significantly lower for 00BX 11-115 and Post 90. No aphid mortalities occurred on any of the entries during the study.

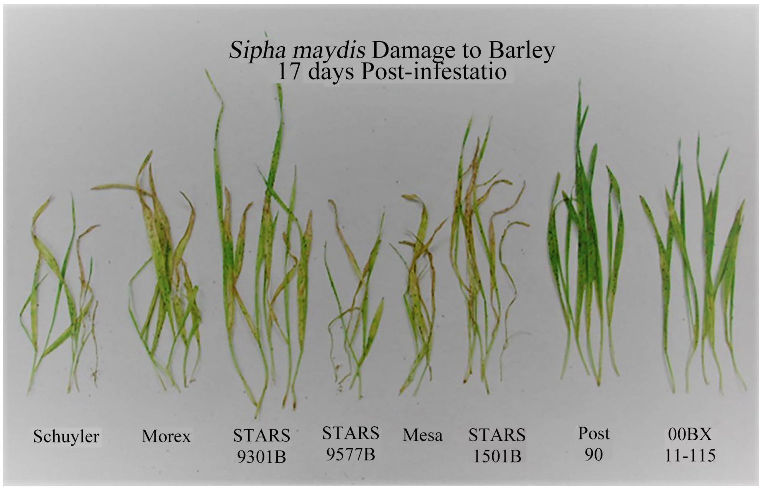

Figure 1. Images of damage rating results from HGA feeding on resistant and susceptible barley entries. The damage rating scale was 1 - 9 where 1 is a healthy plant showing no chlorosis and 9 is a dead chlorotic plant (Burd *et al.*, 1993).

Table 2. Antixenosis, plant damage rating and percent reductions in seedling height and leaf number.

Entry	Antixenosis*	Plant damage rating**	Reduction in seedling height	Reduction in leaf number
	Aphids/seedling		%	%
STARS 9301B	96.3 4.9b	6.5 0.3b	54.9 3.6b	33.3 0.0a
STARS 9577B	69.0 6.2c	7.8 0.4a	57.0 2.5ab	33.3 0.0a
Mesa	59.1 4.7c	8.4 0.2a	55.8 2.5ab	30.0 3.3a
00BX 11-115	43.3 7.1e	2.2 0.2c	47.9 2.6c	30.0 3.3a
Post 90	44.1 6.9e	2.5 0.3c	54.6 2.0bc	30.0 3.3a
STARS 1501B	93.0 5.1b	6.6 0.2b	52.8 2.2bc	33.3 0.0a
Morex	127.2 8.1a	7.8 0.3a	53.2 3.0bc	26.7 4.4a
Schuyler	63.3 5.8c	6.8 0.6b	61.9 3.5a	33.3 0.0a

* Means within a column followed by a different lower-case letter are significantly different ($P \leq 0.05$). **1 - 3 = highly resistant, 4 - 6 = moderately resistant to moderately resistant, and 7 - 9 = susceptible.

Table 3. Effects of entry on HGA intrinsic rates of increase (r_m) and its components.

Entry	Days to reproductive adult*	Fecundity rate	Intrinsic rate of increase
	d	M_d	r_m
STARS 9301B	10.5 0.1abc	38.7 0.3b	0.252 0.003bc
STARS 9577B	10.2 0.1c	38.1 0.7b	0.264 0.002b
Mesa	9.7 0.4d	38.2 0.6b	0.278 0.004a
00BX 11-115	10.8 0.3ab	28.8 0.4d	0.230 0.007d
Post 90	11.0 0.1a	29.6 0.6d	0.227 0.003d
STARS 1501B	10.3 0.1c	32.3 0.8c	0.249 0.001c
Morex	9.7 0.2d	42.6 1.0a	0.288 0.006a
Schuyler	10.4 0.1bc	37.9 0.9b	0.258 0.003bc

* Means within a column followed by a different lower-case letter are significantly different ($P \le 0.05$).

4. Discussion

Significant and substantial differences in plant damage response among entries occurred when challenged by HGA infestation. 00BX 11-115 and Post 90 were the only entries which expressed strong resistance to feeding damage while other entries suffered much higher plant damage that clearly reflected susceptibility to HGA (**Table 1**, **Figure 1**). 00BX 11-115 and Post 90 also expressed high levels of antixenosis and antibiosis (r_m) in comparison to susceptible entries. Closer examination of HGA feeding damage after six days on susceptible Morex revealed numerous feeding sites with dark necrosis and extensive chlorosis. These distinctive types of feeding damage have also been described for another phytotoxic cereal aphid, the greenbug, feeding on wheat [25] [26]. In contrast, feeding sites on resistant Post 90 had very limited necrotic lesioning with adjacent cell bleaching and limited chlorosis (**Figure 1**). Post 90 is the greenbug resistant parent of 00BX 11-115. They share the single dominant greenbug resistant gene, *Rsg*1, which suggests this gene may be responsible for cross-resistance to HGA. Not all greenbug resistance genes are cross-resistant to HGA. STARS 1501B which carries the other identified single dominant greenbug resistance gene, *Rsg*2, was susceptible to feeding damage and was among the entries with the lowest levels of antixenosis and antibiosis.

Greenhouse seedling resistance ratings have been shown to accurately predict field resistance in terms of grain yield for RWA [27]. In 2007 [3] reported HGA in the ligula area of flag leaves in the late spring where chlorosis reduced functional leaf area and inhibited head growth. Although substantial reductions in seedling height and leaf number occurred in all entries, these kinds of reductions due to severe infestation levels in caged plant trials are common regardless of resistance or susceptible status [13] [22] [28], however 00BX 11-115 and Post 90 withstood high infestations in the caged conditions of this study and remained green and only slightly damaged while the other entries sustained severe chlorosis and were near death. Future studies need to be conducted to establish that resistance in 00BX 11-115 and Post 90 persists throughout the life of the plant and offers meaningful resistance in terms of grain yield in the field.

In 2019, [6] reported that HGA is currently present in low numbers in the Rocky Mountain and Southern Plains regions of the US and suggests that it is in the early stages of adaptation to these areas. It was also reported that there is a general lack of predators and parasites that could naturally help regulate HGA. Development of resistant cultivars would be the most economically and environmentally sound defense against this newly introduced pest. Cross-resistance identified in greenbug resistant sorghum [12] has been utilized to immediately deploy cultivars and fast track development of new resistant cultivars to a recently introduced pest of sorghum, the sugarcane aphid. Identification of cross-resistance in 00BX 11-115 (soon to be released as the cultivar Fortress) and Post 90 provides an opportunity to quickly deploy and develop cultivars resistant to HGA.

5. Conclusion

From the eight genotypes of which 6 were known to have resistance to either RWA or GB, only the Post 90 which has the *Rsg*1 resistance gene, and 00BX 11-115 which has both *Rsg*1 and an undetermined *Rdny* are known to be resistant to both GB and RWA. We determined in this experiment that Post 90 and 00BX 11-115 were also resistant to the HGA. Discovery of these sources of resistance will allow time for the further development and deployment of more resistant sources of barley to provide growers with resistant genotypes that will prevent loss in yield and perhaps decrease the chance for the spread of barley yellow dwarf virus, the most devastating viral disease in barley. The economics of having resistant aphid sources for this particular aphid species infesting barley has not determined however numerous examples of significant positive economic impacts of providing resistant cereal grains against virulent cereal aphids exist.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Abbreviations

d, day;
L:D, light: dark;
rm, intrinsic rates of increase;
RWA1, Russian wheat aphid Biotype 1;
RWA2, Russian wheat aphid Biotype 2.