Yield Effects of *Barley yellow dwarf virus* in Soft Red Winter Wheat

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ABSTRACT

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Three cultivars of soft red winter wheat were evaluated to determine the relationship between the incidence and time of infection by *Barley yellow dwarf virus* (BYDV) and yield. Wheat was planted in 1995, 1996, and 1997 in a split-plot design with six replicates at sites in Indiana and Illinois. Yield plots were infested with different amounts of viruliferous aphids, and the incidence of BYDV in each plot was measured. In a 2-year study in Illinois with cv. Clark and the PAV-IL isolate of BYDV, yields were assessed following aphid infestation in fall, early spring, and late spring. Early spring infections resulted in larger yield reductions than late spring infections in both years and larger than fall infections in one year. Regression analyses to relate incidence of infection and yield with data

from fall and early spring infections provided R^2 values of 0.89 and 0.51 for the 1996 to 1997 and 1997 to 1998 seasons, respectively. An additional study at the same site in the 1996 to 1997 season compared the yield responses of cvs. Clark, Y88-3e, and PT8935b. Increases in the incidence of BYDV correlated with decreases in yield, with R^2 values of 0.80, 0.78, and 0.90 for the three cultivars, respectively. Estimated yield losses in both studies and all cultivars ranged from 27 to 45 kg/ha or 0.34 to 0.55% for each percent increase in virus infection. In a third study over a 2-year period in Indiana with the same three wheat genotypes and a second BYDV isolate (PAV-P), BYDV treatments resulted in significant reductions in yield, but yield loss and the incidence of BYDV were not linearly correlated. Given the differences in yield reductions caused by the two BYDV isolates, PAV-P may be an attenuated strain of BYDV and may cross-protect plants from naturally occurring strains of the virus.

Barley yellow dwarf (BYD) is a globally important virus disease of cereal crops (4). Because of its worldwide impact on cereal crop production, this disease and its causal agent *Barley yellow dwarf virus* (BYDV) have been intensively studied. The virus is endemic to all the major wheat growing regions of the world, including the winter wheat growing areas of the United States. Numerous studies have described yield effects and the economic impact of the virus in wheat (1,2,5,6,10,11,14,17,18,21,22,25,27,30). Yield losses of up to 80% have been reported (26); this varies greatly with the isolates of the virus, the cultivar of wheat, time of infection, and environment factors. Because most estimates of BYDV incidence and the effects of the disease have been based on visual symptoms, the accuracy of these estimates is limited. Infections of BYDV may give rise to symptoms such as stunting, reduced root growth, reduced tillering, and leaf discoloration (yellowing), but in wheat, infections may be asymptomatic and still reduce yields.

The epidemiology of BYDV and its aphid vectors have been studied for decades, and 25 species of aphids have been reported to vector BYDV (8). The aphid species most important in the U.S. for transmitting the common strains of BYDV is the oat bird-cherry aphid, *Rhopalosiphum padi*, although in some regions *Sitobion avenae* and *Schizaphis graminum* (the Greenbug) are commonly found on small grains (13). An environment factor of particular significance to the epidemiology of the disease is the temperature during the period in which seedlings become established. Varying the planting date is a common agronomic practice to avoid the period when the aphid vectors are most active. For

winter wheat, warm, dry weather conditions during the fall growth period enhance the spread of aphids and virus.

In the United States, a majority of growers do little to control the incidence and spread of BYDV in winter wheat other than delay planting to minimize vector activity. In years with mild fall temperatures, aphids remain active during seedling growth, resulting in virus transmission and a higher incidence of disease. Although it is known that BYDV can cause significant yield loss, economic thresholds for BYDV infection have not been established. A limiting factor in obtaining data on the impact of the disease is the prevention of BYDV infection in control plots. This has recently been addressed through use of the systemic insecticide imidacloprid (Gaucho) in combination with foliar sprays to limit infection (14,15). Imidacloprid is an effective aphicide when applied as a seed treatment to spring- and fall-planted cereal crops. Treatment effectively kills aphids for 6 to 8 weeks after sowing. In the upper Midwest wheat-growing regions of the U.S., this is often sufficient time to protect the fall-planted crop from BYDV infection until temperatures become cold enough to eliminate aphid activity. In addition to imidacloprid, newer generation synthetic pyrethroids are useful in controlling the spread of BYDV, facilitating assessments of yield effects (21).

The question of how fall versus spring infection of BYDV affects yield in winter wheat has not been thoroughly studied, although a number of reports have addressed this issue (5,6,25). It is generally acknowledged that limiting the fall infection of a winter wheat crop will reduce yield loss, but the level of incidence and time of infection and the resulting economic loss has not been determined. Fall-infected wheat plants may be more susceptible to winter cold injury and contribute to losses (25). Infected wheat and grassy weeds can serve as reservoirs of the virus in the early spring as nonviruliferous aphids fly into and colonize wheat fields. Although fall-infected winter wheat can func-

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tion as a source of inoculum, it is not clear how this ultimately influences the epidemiology of the disease and yield loss. In this study of soft red winter wheat, the goal is to quantify the relationship between the time of infection and incidence of BYDV and effects on yield.

MATERIALS AND METHODS

Wheat cultivars, virus strains, and aphid vectors. The three soft red winter wheat cultivars used in this study were the commercially available cv. Clark (24) and cvs. PT8935b and Y88-3e (Hybritech Seed International, Lafayette, IN). The strains of BYDV were regional isolates of the PAV serotype, PAV-IL (BYDV-PAV-IL; 9) and PAV-P (BYDV-PAV-P; 28). BYDV-PAV-IL was used at the Illinois test site, and BYDV-PAV-P was used at the Indiana test site. Viruses were maintained in oat cv. Clintland-64 in association with viruliferous colonies of *Rhopalosiphum padi* L. Aphid adults and nymphs of all stages were used to infest and infect plants.

Yield plots and insecticides. Yield plots were planted in a split-plot design with the three cultivars as main plots and the BYDV treatments (aphid infestation dates and levels) as subplots with six replicates in each block. Planting dates were the last week in September or the first week in October in West Lafayette, Indiana and Urbana, Illinois. The date of the study indicates the summer of harvest, e.g., the 1996 study was planted in September 1995 and harvested in July 1996. Plots consisted of seven rows, 15 cm apart (Indiana) or six rows, 18 cm apart (Illinois), and 2.4 m in length. Plot size was 2.88 (Indiana) and 3.12 m² (Illinois), and seeding density was ≈ 376 (Indiana) and 397 kernels m⁻² (Illinois). Seed for the control plots was treated with imidacloprid (Gaucho) as a coating at a rate of 1.2 g a.i./kg of seed. One or two spring foliar sprays of dimethoate (Cygon) were applied at a rate of 280 g a.i./ha in 233 liters of water. To minimize yield reductions due to fungal diseases, propiconazole, 1-([2-{2,4-dichlorophenyl}-4-propyl-1,3-dioxolan-2-yl]methyl)-1H-1,2,4-triazole (Tilt) was applied at Feekes GS 8 at the rate of 20 ml a.i./ha in 187 liters of water. Plots were harvested individually with a research combine, and yield equivalents were calculated.

Experiments, years of study, and locations. To measure the impact of fall versus spring virus infection, randomized blocks of plots were planted with the cv. Clark and assigned one of four treatments: (i) fall application of viruliferous aphids, (ii) early spring application of viruliferous aphids, (iii) late spring applications of viruliferous aphids, or (iv) a control of an insecticide treatment without applied aphids. The goal when applying aphids was to achieve 100% infection. This timing of BYDV infection study was carried out in 1997 and 1998 in Illinois. To assess the impact of BYDV on yield in three cultivars of wheat, three levels or amounts of viruliferous aphids were introduced into randomized plots. The goal was to achieve low (10%), medium (30%), and high (50%) levels of infection. This level of infection study was conducted in 1996 and 1997 in Indiana and in 1997 in Illinois. Data from all studies were used in analyses to quantify the relationship between virus incidence and crop yield.

Infesting plants with viruliferous aphids. To inoculate wheat plots, viruliferous aphids were shaken off infected plants on a tray covered with a preweighed amount of talc, cornmeal, or talc and cornmeal. Aphids were gently mixed in the cornmeal, their weights (or in some cases volume) were estimated, and the mixture was held at 4°C until used (up to 24 h). Teaspoon measures (≈ 5 ml) of aphids in cornmeal mix were counted to estimate the numbers of aphids per volume. The aphid and cornmeal mixture was transferred to a fabricated saltshaker (capped cylinder with 2 mm holes drilled in lid) and sprinkled on wheat plots. For studies in which the objective was to achieve 100% infection, $\approx 1,540$ aphids were applied to each plot. The number of aphids required to achieve lower levels of infection were empirically deter-

mined and are described below. The fall aphid infestations were done ≈ 4 weeks after planting at tillering, Feekes growth stage 3 (19). The early spring infestations were done in the last week of March or the first week of April at Feekes growth stage 4 (early stem elongation); the late spring infestations were done 4 weeks later at Feekes growth stage 8 (flag leaf appearance). Four to seven days after all infestations, plants were sprayed with dimethoate to minimize the spread of the virus.

Enzyme-linked immunosorbent assay for detection of BYDV, incidence of infection estimates, and statistical analyses. In the 1996 study, 60 whole tillers were sampled systematically from all of the plots in early spring (April) when plants were just beginning regrowth following winter dormancy. Samples were stored at -70°C until assayed. Approximately 50 mg of leaf tissue (composite of three leaves from each tiller) was ground in a microcentrifuge tube by an overhead stirrer with a piston adapted to fit the sampling tube. Tissue was ground in 750 μ l of phosphate-buffered saline (PBS) plus 0.05% Tween 20 (PBST), e.g., 15:1 buffer/tissue ratio (7). Ovalbumin (0.2%, wt/vol) in PBST was used as a blocking agent prior to adding plant sap to the enzyme-linked immunosorbent assay (ELISA) plates. Samples were processed with a double antibody sandwich ELISA (7). Antibodies against BYDV-PAV and cereal yellow dwarf virus isolate RPV (CYDV-RPV, formerly known as BYDV-RPV; 20) were purchased from the American Type Culture Collection (Rockville, MD) or developed by Monsanto (Monsanto Company, Chesterfield, MO). For the 1997 and 1998 studies, sampling was delayed until early June, ≈ 4 weeks before harvest. Sixty tillers with spikes were sampled systematically from all of the plots. The sample used for analysis consisted of 40 to 60 mg of glume tissue, ≈ 8 glumes collected from the same spike. To facilitate grinding, the glumes were frozen on dry ice and crushed with a pestle prior to being ground with buffer, as described above. Extracts from uninfected, growth chamber-grown leaves or glumes served as negative controls, while BYDV-PAV or CYDV-RPV standards purified from oats (16) were included on each plate as positive controls. ELISAs were performed to measure the incidence of CYDV-RPV from natural infections, and the same 60 plant extracts per plot were tested for both viruses. Samples were considered positive for BYDV if absorbance values were greater than the average negative control plus three standard deviations; these absorbance values were generally greater than 0.07. The threshold of detection for BYDV standards was between 0.5 and 1.0 ng. The incidence of virus infection in the yield plots was estimated as the percentage of ELISA positive samples in the total of 60. Data were analyzed using the SAS statistical package StatView (SAS Institute Inc., Cary, NC).

RESULTS

Timing of BYDV infection and yield. To measure the impact of fall versus spring virus infection, viruliferous aphids carrying the local isolate BYDV-PAV-IL were employed, and aphid infestations at three different times were done in the same manner, with the goal to achieve 100% infection. The incidence of virus infection was measured in every plot (24 total) in the study by sampling 60 plants from each plot and testing them individually for virus by ELISA. Glume tissue was used for these assays in 1997 and 1998, because it (as opposed to flag leaf or other foliar tissue) gave the highest ELISA readings (data not shown). The incidence observed with fall and early spring infestations in 1997 and 1998 ranged from 74.7 to 81.7% (Table 1). Late spring infestations resulted in a lower incidence of infection than the earlier infestations in 1997; in the 1998 study, differences between the incidence of infection in the late spring and early spring infections (64.7 and 81.1%, respectively) were not statistically significant ($P = 0.11$). Significant reductions in yield ($P \leq 0.02$) were observed in all plots treated with BYDV. The greatest effects were seen following

fall and early spring infection, with yield reductions ranging from 23.8 to 35.3%. In 1998, the early spring infection resulted in significantly larger yield decreases than the fall infections (23.8 versus 33.2%, $P = 0.011$). Yield reductions following late spring infections were significantly smaller than those seen when infection occurred in the fall and early spring.

Multiple levels of BYDV infection from fall infestation with different numbers of aphids. In preliminary greenhouse tests, aphids were applied to flats of wheat, and the number of infested plants were counted to determine empirically the number required to achieve different levels of infestation. Based on an estimated planting density of 1,120 plants per plot, ≈ 64 , 192, and 320 mg of aphids were necessary to achieve 10, 30, or 50% of plants infested by one or more aphids; these weights represent ≈ 240 , 720, and 1,200 aphids, respectively. These treatment levels were designated low, medium, and high, respectively. A plot planted with insecticide-treated seed but not receiving aphids served as a control. Viruliferous aphids carrying the isolates BYDV-PAV-IL and BYDV-PAV-P were applied to plots in Illinois and Indiana, respectively. Leaf and glume tissue were tested by ELISA to estimate the incidence of the virus. The incidences of BYDV-PAV in the 1996 and 1997 seasons are shown in Table 2. Data are not presented for the Illinois site in 1996 because these plots were lost to winter injury. At the Indiana site in 1996, four levels of virus infection were obtained with clearly separable means; the means are shown in Table 2 and estimated at 26 to 30% (low), 44 to 48% (medium), and 65 to 78% (high). This contrasts with incidence levels obtained during the 1997 season at both the Illinois and Indiana sites. Different levels of infection were obtained, but for several treatments confidence intervals overlapped and mean incidence levels did not differ significantly ($P = 0.05$).

The background levels of BYDV-PAV due to natural infection in 1996 appeared lower than in 1997 (Table 2). The mean incidence of BYDV ($\pm$ standard error) in the insecticide-treated controls at the Indiana site in 1996, averaged for all three cultivars, was $1.2 \pm 0.7\%$. This compares with $8.3 \pm 1.1\%$ and $10.5 \pm 1.6\%$ mean incidence in these controls in 1997 at the Indiana and Illinois sites, respectively. In addition, natural BYDV-PAV infection was measured in untreated control plots in 1997; the mean incidence averaged for the three cultivars was $24.4 \pm 2.5\%$ and $47.8 \pm 2.5\%$ at the Indiana and Illinois sites, respectively. It is expected that the higher incidence of natural BYDV infection would have confounded the results from treatments designed to achieve desired levels of BYDV in infested plots.

Yield loss and the incidence of BYDV-PAV-IL in Illinois. At the Illinois site in 1997, yields of all three cultivars decreased with an increasing incidence of BYDV-PAV-IL (Table 2). The incidence of BYDV in infested plots ranged from 34.5 to 54.5%, significantly higher than those in the insecticide-treated control plots that ranged from 6.9 to 14.4%. The incidence of BYDV-PAV in natural infection plots (those without insecticide treatments) ranged from 45.2 to 51.9%; these values did not differ significantly from the BYDV-treated plots. The yields in these natural infection plots were as low or lower than those in BYDV-treated plots. Levels of the CYDV-RPV in the natural infection plots

were also measured in the 1997 study, and the mean incidence was 4.0%.

To quantify the relationship between the incidence of BYDV-PAV-IL and effects on yield, a regression analysis was performed with data from the control and treatments with aphid infestation. There was a remarkable linearity, with R^2 values for the three cultivars ranging from 0.81 to 0.91 (Fig. 1). The estimates of yield losses attributable to BYDV-PAV-IL ranged from 27 to 45 kg/ha for each percent incidence of virus. The respective estimates of yields for plots with no BYDV (y -intercepts in Fig. 1) were 7,895 and 8,180 kg/ha. This corresponds to losses of 0.34 to 0.55% for each percent increase in virus infection.

Similar estimates for the impact of BYDV-PAV-IL on yield were obtained in the time-of-infection study from the data for the fall and early spring treatments (Fig. 2). A regression analyses of data for the controls and the fall and early spring treatments yielded R^2 values of 0.89 and 0.51 for 1997 and 1998, respectively. The data for the late spring treatment were not included because this time of infection affected yields differently than the fall and early spring infections. The effects of the virus on yield were estimated at 31 and 21 kg/ha for each percent increase in BYDV in 1997 and 1998, respectively. This corresponds to yield losses of 0.45 and 0.37% for each percent incidence of BYDV, respectively. These values are within the range of values described above for the 1997 study comparing the responses of the three cultivars.

Wheat yields in plots infected with BYDV-PAV-P. As observed at the Illinois site, yields of all three cultivars in Indiana were reduced in BYDV treated plots (Table 2). Although yield reductions were apparent, the relationship between virus incidence and yield was not linear; increasing levels of virus did not correlate with decreases in yield in the 1996 and 1997 seasons. The R^2 values in plots of yield versus incidence (percent) of BYDV were calculated for cvs. Clark, Y88-3e, and PT8935b to be 0.39, 0.062, and 0.259 in the 1996 season and 0.45, 0.002, and 0.083 in the 1997 season, respectively. The major difference between the Indiana and Illinois studies, aside from edaphic and micro-environmental factors, was the selection of the regional isolate of BYDV-PAV.

In the first year of the study, the level of natural infection was not measured, but it can be inferred from the insecticide-treated controls as being low relative to that observed in 1997 (Table 2). In the second year of the study (1997), the natural infection of BYDV-PAV in Indiana was measured in plots that did not receive any insecticide treatments, and the mean incidence ranged from 20.3 to 31.4%. These levels of BYDV-PAV were comparable with or lower than those in the BYDV-treated plots (Table 2). Despite this fact, yields in the natural infection plots were as low or lower than in the BYDV-treated plots, suggesting that the naturally occurring strains of BYDV affected yields more severely. This is supported in part by a regression analysis using data from the control and natural infection plots for the cv. Clark which yielded an R^2 value of 0.748 (plot not presented). The analogous R^2 values for cvs. Y88-3e and PT8935b were 0.326, and 0.23, respectively. The incidence of naturally occurring CYDV-RPV in the natural infection plots during the 1997 season was very low, averaging only 6.7%.

TABLE 1. Incidence of *Barley yellow dwarf virus* (BYDV) infection and yield of wheat following fall, early spring, and late spring infestations with viruliferous aphids in Illinois^a

Time of Infection	Mean % incidence of BYDV		Yield (kg/ha)		% Yield reduction	
	1997	1998	1997	1998	1997	1998
Control	10.0 $\pm$ 1.3 a	32.2 $\pm$ 7.0 a	6,689 $\pm$ 169 a	5,404 $\pm$ 198 a	...	...
Fall	74.7 $\pm$ 1.7 c	81.7 $\pm$ 6.5 b	4,702 $\pm$ 138 c	4,118 $\pm$ 67 c	29.7 a	23.8 b
Early spring	81.3 $\pm$ 4.3 c	81.1 $\pm$ 5.3 b	4,327 $\pm$ 65 c	3,612 $\pm$ 27 d	35.3 a	33.2 a
Late spring	30.6 $\pm$ 3.7 b	64.7 $\pm$ 8.5 b	6,182 $\pm$ 119 b	4,916 $\pm$ 148 b	7.6 b	9.0 c

^a Means are shown as percent values $\pm$ the standard error. Values followed by the same letter within incidence, yield, and yield reduction columns are not significantly different according to Fisher's protected LSD ($P \leq 0.05$).

DISCUSSION

There were two primary goals in this study of BYDV in soft red winter wheats: (i) to quantify the relationship between the incidence of BYDV and effects on yield; and (ii) to evaluate the impact of the time of virus infection on yield. A relatively unique contribution of the study is the combined release of viruliferous aphids to give different levels of infection, and the large scale sampling and ELISA testing to provide an accurate measure of disease incidence on an individual plot basis; over 20,000 individual plants were tested by ELISA to assess the incidence of BYDV infection.

Previous studies indicate that fall infection with BYDV reduced yield to a greater extent than infections occurring in the spring (5,6,25). Our results for the time of infection study indicate not only that there may be little difference between fall and early spring infections, but that in some cases, spring infections can be more severe. Rather than viewing these results as inconsistent with past studies, they emphasize that responses differ depending on the cultivars, virus strains, and the season. Generalizations on yield effects need to be tempered by a recognition that a large number of biotic and abiotic environmental factors will interact to

determine yield. This study has minimized some of the variables by focusing on one cultivar. Although only one serotype of BYDV was employed, there was considerable biological variability even within the same serotype. In fall-infected crops, one factor that might influence yield is the interaction between BYDV and winter severity, because the virus has been suggested as predisposing plants to winter injury (25). Of all the infestation trials, yield effects were least severe with late spring infestations, consistent with the study of McKirdy and Jones (22) in which delaying infection or slowing the apparent disease rate correlated with lower reductions in yield. In both years of the study, late spring infestations resulted in fewer detectable infected plants, although the infestation methods were the same as done in the fall and early spring. It may be that with older plants, the virus is less able to systemically infect or to become established in the inflorescence, perhaps due to the effects of more mature vascular tissue. Furthermore, at Feekes growth stage 8 (flag leaf appearance), plants are much larger and the virus is no longer able to significantly dwarf plants, one of the hallmark host effects.

In the 1996 season, aphid infestation methods effectively gave rise to discrete levels of infection. This was not true in the 1997 season when there was much greater variability, with broadly overlapping estimates for incidence. This was due almost certainly to the higher background levels of natural infection at both sites, as indicated by the higher incidence of virus in the control plots. In this study, we did not monitor extensively for additional serotypes of BYDV or CYDV. In the north central region of the U.S., BYDV-PAV and CYDV-RPV are the predominant serotypes (13; K. Perry, *unpublished data*). The anti-BYDV-PAV serum employed in ELISA would have detected, but not discriminated between, the three serotypes PAV, MAV, and SGV. Results from analyses of both the Indiana and Illinois sites in 1997 suggest the impact of CYDV-RPV in that year was minimal.

The magnitude of the effect of BYDV on yield has been quantified for the cv. Clark during the 1997 and 1998 seasons and for two additional cultivars in the 1997 season. The measured loss was a function of the yield potential of the variety and the cropping season. In all cases, estimates of yield loss due to the BYDV-PAV-IL isolate were in a narrow range of 0.34 to 0.55% for each percent increase in virus infection. In portions of the north central region of the U.S., soft red winter wheat yields average $\approx 4,032$ kg/ha (12). A loss of 0.5% represents ≈ 20 kg/ha, a value remarkably similar to values calculated from the data of McKirdy and Jones (21) of 0.49% and 20 kg/ha, and to the undocumented estimate of 20 to 50 kg/ha described in a review by Miller and Rasochova (23).

An unexplained aspect of this study is the results from the yield plots in Indiana infected with BYDV-PAV-P. Decreases in yield correlated with treatments (i.e., control- and insecticide-treated plots vs. aphid-infested plots), but increasing the levels of BYDV-PAV-P did not give rise to commensurate losses in yield. This response was observed in all three cultivars and in both years of the study. One likely rationale is that BYDV-PAV-P is an attenuated isolate with a limited ability to reduce growth and yield potential. This isolate has been maintained in plants in growth chambers for nearly two decades, and changes in virulence under these conditions would not have been apparent. Yield losses in the aphid-infested plots may have been due to infection by naturally occurring BYDV strains. Losses in the controls would have been minimized by the insecticide treatment. Infection by BYDV-PAV-P may or may not have affected yields, but regardless, could have acted to cross-protect plants from the effects of the naturally occurring BYDV infections. Cross-protection among strains of BYDV has been documented, but not always observed (3,29). This explanation is quite plausible for the second year of the study when natural infection levels were high and yields in the natural infection plots were affected, but in the 1996 season, yields in the natural infection plots did not differ significantly from the control

TABLE 2. Wheat yields and incidence of *Barley yellow dwarf virus* (BYDV)^z

Time	Cultivar	Infestation level	% BYDV	Yield (kg/ha)
Indiana 1996	Clark	Control	0.83 a	4,367 a
		Low	29.9 b	3,759 b
		Medium	44.5 c	3,765 b
		High	65.0 d	3,868 b
		Natural infection	NT	4,323 a
	Y88-3e	Control	2.8 a	4,009 a
		Low	25.8 b	3,321 b
		Medium	47.5 c	3,536 ab
		High	65.0 d	3,518 ab
		Natural infection	NT	3,792 ab
	PT8935b	Control	0 a	4,322 a
		Low	27.5 b	3,810 b
		Medium	44.9 c	3,791 b
		High	77.6 d	3,605 b
		Natural infection	NT	4,375 a
Indiana 1997	Clark	Control	8.0 a	5,501 a
		Low	48.0 c	5,035 b
		Medium	64.2 d	5,062 b
		High	75.4 e	4,859 bc
		Natural infection	31.4 b	4,662 c
	Y88-3e	Control	7.8 a	5,857 a
		Low	48.9 b	5,377 bc
		Medium	66.1 c	5,645 ab
		High	76.7 c	5,732 ab
		Natural infection	21.5 a	5,047 c
	PT8935b	Control	9.0 a	5,872 a
		Low	29.8 bc	5,519 ab
		Medium	47.8 c	5,468 b
		High	69.4 d	5,530 ab
		Natural infection	20.3 ab	4,888 c
Illinois 1997	Clark	Control	14.4 a	6,980 a
		Low	35.0 ab	6,054 b
		Medium	47.7 b	5,605 bc
		High	54.5 b	5,451 c
		Natural infection	51.9 b	5,357 c
	Y88-3e	Control	6.9 a	7,800 a
		Low	38.0 b	6,868 bc
		Medium	41.7 b	6,686 bc
		High	50.5 b	6,550 bc
		Natural infection	45.2 b	6,318 c
	PT8935b	Control	10.0 a	7,794 a
		Low	34.5 b	6,581 b
		Medium	47.9 bc	6,091 bc
		High	51.7 c	5,786 c
		Natural infection	46.1 bc	5,970 bc

^z Values followed by the same letter within the same column are not significantly different according to Fisher's protected LSD ($P \leq 0.05$). NT indicates the incidence of BYDV was not tested.

Fig. 1. Regression analysis of yields (kg/ha) in three cultivars of wheat in relation to the incidence of *Barley yellow dwarf virus* (BYDV) in Illinois in 1997. Plots of cvs. **A**, Clark, **B**, Y88-3e, and **C**, PT8935b were infested with viruliferous aphids in the fall of 1996, and yield measurements were made the following summer. Data are included for six replicates of each of four aphid infestation treatments: control, low, medium, and high. Grain yield and BYDV incidence were determined by individual testing of 60 plants per plot by enzyme-linked immunosorbent assay.

plots. Another possible explanation for the yield responses observed at the Indiana site is that factors other than BYDV, such as soil moisture or other diseases, may have limited yield and masked effects attributable to BYDV. For example, in 1996 there was a significant incidence of scab (caused by *Gibberella zeae*) in the plots.

It is generally thought that in many areas of the U.S. BYDV chronically affects wheat at low levels of a few percent in most years. The problem with this and most previous estimates of incidence is that they are based on a visual evaluation of symptoms, and BYDV infections in wheat are notoriously variable, often without any obvious symptoms. Earlier studies designed to evaluate the impact of BYDV on yield have shown differences in treatment effects, but they have been limited by the sizes of the test plantings and accurate assessments of incidence. A notable exception is the work on wheat production in Western Australia by McKirdy and Jones (21,22), who monitored plots extensively to measure the levels of natural BYDV infection.

Fig. 2. Regression analysis of wheat yield (kg/ha) in Illinois in relation to the incidence of *Barley yellow dwarf virus* (BYDV) inoculated at two times during the growing season. Plots of cv. Clark were infested with viruliferous aphids in the fall and early spring of the **A**, 1996 to 1997, and **B**, 1997 to 1998 seasons. There were six replicated plots for each treatment and an insecticide-treated control at each time of inoculation. Grain yield measurements were made for each plot, as well as, determinations of BYDV incidence by the individual testing of 60 plants per plot by enzyme-linked immunosorbent assay.

It remains to be determined if the level of impact described in this study is representative of what is encountered in different areas of the U.S. and other parts of the world where wheat cultivars and serotypes or strains of BYDV vary. In order to predict regional losses due to this disease, information on the incidence of the virus will be required, in addition to, an impact factor such as percent yield loss for each percent BYDV. Nonetheless, this study provides a well substantiated foundation to build accurate yield loss assessments for this small grains disease of world-wide importance.

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LITERATURE CITED

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