Use of Imidacloprid as a Seed-Treatment Insecticide to Control Barley Yellow Dwarf Virus (BYDV) in Oat and Wheat

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ABSTRACT

Gourmet, C., Kolb, F. L., Smyth, C. A., and Pedersen, W. L. 1996. Use of imidacloprid as a seed-treatment insecticide to control barley yellow dwarf virus (BYDV) in oat and wheat. Plant Dis. 80:136-141.

Control of barley yellow dwarf was studied in six-row plots of two oat cultivars using three rates (0.6, 1.2, and 1.8 g a.i. kg^{-1} seed) of imidacloprid, a seed-treatment insecticide. All insecticide treatments decreased the percentage of infected plants. Yield increases of up to 112% were observed in treated plots of a moderately susceptible cultivar inoculated with viruliferous aphids carrying barley yellow dwarf virus BYDV-PAV-IL. Insecticide-treated plots of a tolerant cultivar inoculated with BYDV-PAV-IL yielded up to 23% more than nontreated plots. In a similar study with four soft red winter wheat cultivars, all insecticide treatments decreased the percentage of infected plants, with the highest dose providing the most protection against BYDV infection. Yields were increased up to 21% in treated plots of a susceptible cultivar inoculated with viruliferous aphids carrying BYDV-PAV-IL. Noninoculated insecticide-treated plots also yielded an average of 14% more than noninoculated nontreated plots.

Oat (*Avena sativa* L.) and wheat (*Triticum aestivum* L.) in the United States are affected by barley yellow dwarf (BYD), one of the most economically important viral diseases of small grains (5). Symptoms of BYD in wheat are subtle and consist primarily of chlorosis and stunting. In contrast, symptoms are more severe in oat, where reddening of the leaves and blasting of the florets are easily observed.

Many researchers have shown that barley yellow dwarf virus (BYDV) can cause significant yield losses in spring oat (27,32) and winter wheat (*T. aestivum* L. em Thell) (7,13). Yield reductions often occur due to infection by one or more strains of BYDV, a group of phloem-limited luteoviruses obligately vectored in a circulative manner by several species of aphids (14,35). In the U.S. Midwest, the most prevalent and devastating strain of the virus is PAV, a nonspecifically transmitted strain vectored by both the English grain aphid (*Sitobion avenae* F.) and the oat bird-cherry aphid (*Rhopalosiphum padi* L.) (28). In spring oat, infection from viruliferous aphids occurs in the spring; whereas in wheat, infection may occur either in the fall just after wheat is sown or in the spring.

The control of BYDV is an important consideration in the production of oats and wheat in the United States. Important sources of tolerance are continually being identified (6,19,31), but no cultivars immune to the virus have been developed.

Various insecticides, including synthetic pyrethroids, organophosphates, and carbamates, have been developed for the control of aphids (17,18,20,24). These insecticides are usually applied at Zadoks growth stage 14 or 15 (37) to avoid phytotoxicity. When aphid populations are high prior to these stages, these insecticides are not effective in preventing transmission of the virus. A seed-treatment insecticide posing low risk to nontarget organisms, causing no phytotoxicity, and systematically translocated in the plant would provide control of aphids from the day the seedling emerges from the ground.

Imidacloprid (1-[(6-chloro-3-pyridinyl) methyl]-*N*-nitro-2-imidazolidinimine) is a nitroguanidine, a new class of insecticides (12,30). Like organophosphates, carbamates, and pyrethroids, imidacloprid is a stomach insecticide which interferes with the transmission of nerve impulses, leading to permanent excitation and death (2). Imidacloprid is the common chemical name for GAUCHO™ insecticide, a contact and systemic insecticide (12) applied as a seed treatment. It has been tested successfully against aphids in such crops as cotton (*Gossypium* sp.), sugar beet (*Beta vulgaris* L.), wheat, and barley (*Hordeum vulgare* L.) (1,11,25).

This paper describes field experiments that examined the effectiveness of imidacloprid applied as a seed treatment to control BYD in oat and wheat. Different application rates of imidacloprid were used and compared to control plots where no insecticide was applied to the seeds.

MATERIALS AND METHODS

Virus isolate and aphid vector. Laboratory clones of *R. padi* maintained on BYDV-PAV-IL infected barley cultivar Hudson were provided by the USDA Cereal Virology facility at the University of Illinois at Urbana-Champaign. Late instar or apterous viruliferous adults infested with the BYDV-PAV-IL isolate were used. The BYDV-PAV-IL isolate has been characterized (16).

Cultivars. Two oat cultivars (Ogle and Don) and four wheat cultivars (Cardinal, Pioneer Brand 2510, Clark, and Pacer) were evaluated. Ogle is a high-yielding and widely adapted cultivar with good tolerance to BYDV (3). Don is a high-yielding and early-maturing cultivar that is moderately susceptible to BYDV (4). The term tolerance is used to describe a host that can be infected by a virus and in which the virus can replicate, but which shows no symptoms or only mild symptoms and little or no loss in yield (9). The term susceptible is used to describe a host that responds to virus infection and replication by showing severe chlorosis, dwarfing, and considerable yield loss. All four wheat cultivars are adapted for production in the midwestern United States, but none of the cultivars tested are known to be tolerant to BYDV.

Field study. Three rates of imidacloprid (GAUCHO™, Gustafson, Inc., Dallas, TX), 0.6, 1.2, and 1.8 g a.i. per kg of seeds, and seeds with no insecticide were tested for 2 years in a split-plot design with four replications where main plots were inoculated (viruliferous aphids were spread on the plants) and noninoculated (no aphids were spread on the plants). Combinations of cultivars and rates were completely randomized within the main

This research was partially funded by Gustafson, Inc.

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Accepted for publication 7 November 1995.

Publication no. D-1995-1218-04R

plots. Blocks of inoculated plots were separated from noninoculated plots by at least one six-row buffer plot. Seeds were planted in six-row field plots, using a six-row cone-type planter, at the Agronomy-Plant Pathology South Farm of the University of Illinois at Urbana-Champaign. Experimental plots were 1.1 × 4.3 m. Oat plots were seeded on 7 April 1992 and 20 April 1993; wheat plots were seeded on 1 October 1992 and 4 October 1993.

At Zadoks growth stage 13 (three-leaf stage), plants were infected with the BYDV-PAV-IL strain by inoculation with viruliferous *R. padi.* For field plot inoculation, aphids were collected from the infected barley plants and immediately taken to the field plots. Approximately 1,000 aphids were distributed on each 3.9-m^2 plot using a shakerlike cup with holes. Three days were allowed for aphids to feed on the oat or wheat plots before application of dimethoate (*O,O*-dimethyl S-[-N-methylcarbamoylmethyl] phosphorodithioate) spray to kill the aphids. Dimethoate was applied at the rate of 189 liters of water per ha using 3.1 ml of dimethoate per liter of water. In all years (1992, 1993, and 1994), plots were rated for symptom expression at Zadoks growth stage 49. Disease incidence was determined based on the percentage of plants exhibiting symptoms. For example, if 50% of the leaves in a plot showed yellowing or reddening, then the plot was determined to have 50% incidence. Each year, 10 flag-2 leaves from each plot were harvested and stored at –80°C until they could be assayed using the triple-antibody sandwich enzyme-linked immunosorbent assay (TAS-ELISA) (10). For evaluation, sap was extracted with a leaf-sap extractor and immediately used in the TAS-ELISA procedure. Plates were read automatically at 405 nm with an ELISA plate reader (Dynatech MR 700, Dynatech Laboratories, Inc., McLean, VA). Eight samples from noninoculated oats or wheat were run on each ELISA plate as negative controls. Height was measured at Zadoks growth stage 90 (early ripening stage). At harvest, data were collected on grain yield, test weight, 1,000-kernel weight, and tillers m^{-2}; and the number of seeds per tiller was calculated using the following formula: grams $tiller^{-1}$ ÷ single-kernel weight, where grams $tiller^{-1}$ was calculated from grams m^{-2} ÷ tiller m^{-2}. Statistical analyses were performed using the general linear model (GLM) procedure of SAS (29). Means were separated by LSD, using a weighted average of E_a (for whole unit) and E_b (for subunit) appropriate for the split-plot design as outlined by Steel and Torrie (33).

RESULTS

I. Oat experiments (1992 and 1993). The statistical analysis indicated a significant year × treatment interaction, and results are presented separately for 1992 and 1993. Differences in disease incidence, yield, test weight, kernel weight, seeds $tiller^{-1}$, and plant height due to insecticide treatment were all significant, while tillers m^{-2} was not significantly affected. All comparisons of treatment means referred to in the results are based on a probability of 0.05.

1992 study. All three rates of imidacloprid reduced disease incidence of BYD in Don inoculated with viruliferous aphids, compared to the nontreated control plots, while in Ogle only the highest two rates reduced disease incidence (Table 1). For Don, disease incidence in plots treated with the highest rate of insecticide was 51% less than in nontreated plots. Imidacloprid also reduced disease incidence for both cultivars in 1992 for the noninoculated plots, indicating the presence of naturally occurring viruliferous aphids.

Yield was significantly higher in the treated plots than in nontreated plots. In inoculated plots, insecticide-treated plots of Don treated with 1.8 g a.i. kg^{-1} of seeds yielded 112% more than non-insecticide-treated plots (Table 2). For plots without inoculation, the mean yield for the treated plots of Don was 47% higher than that of the nontreated plots. In inoculated plots of Ogle, only the plots treated with the highest rate of insecticide differed from the other treatments, with a 19% higher yield than the nontreated plots.

Test weight and kernel weight in Don were significantly lower in nontreated plots without BYDV inoculation than in treated plots. The calculated number of seeds $tiller^{-1}$ was significantly decreased in the nontreated plots only when compared to plots treated with the highest rate of insecticide; no difference was observed without inoculation. In contrast to Don (susceptible cultivar), the calculated number of seeds $tiller^{-1}$ in Ogle (tolerant cultivar) was not reduced in the nontreated plots compared to the insecticide-treated plots in either inoculated or noninoculated plots. For both Don and Ogle, height was

Table 1. Disease incidence of barley yellow dwarf virus (BYDV)-susceptible oat cultivar Don and BYDV-tolerant oat cultivar Ogle in 1992 and 1993 field plots based on percentage of leaves exhibiting yellowing or reddening

Imidacloprid	Don		Ogle	
(g a.i. kg^{-1})	1992 (%)	1993 (%)	1992 (%)	1993 (%)
Inoculated				
0.0	100 a[z]	60 a	33 a	18 a
0.6	78 b	31 bc	31 a	16 a
1.2	59 c	37 b	17 b	11 a
1.8	49 d	21 c	11 b	8 a
Noninoculated				
0.0	46 a	16 a	16 a	6 a
0.6	8 b	7 a	5 b	6 a
1.2	9 b	6 a	5 b	4 a
1.8	7 b	5 a	4 b	5 a

[z] Within groupings and within columns, means with the same letter are not significantly different at $P = 0.05$.

Table 2. Effects of imidacloprid on yield, test weight, yield components, and height of the BYDV-susceptible oat cultivar Don and the BYDV-tolerant oat cultivar Ogle for the 1992 testing season

Rate (g a.i. kg^{-1})	Yield (kg ha^{-1})	Test wt. (kg m^{-3})	Kernel wt. (g $1{,}000^{-1}$)	Seeds $tiller^{-1}$ (calc.)	Height (cm)
Don inoculated					
0.0	1,654 a[z]	448 a	31 a	7 a	62 a
0.6	2,568 b	432 a	31 a	12 ab	70 b
1.2	2,946 bc	444 a	33 a	13 ab	78 c
1.8	3,504 c	453 a	32 a	18 b	84 d
Don noninoculated					
0.0	3,037 a	416 a	29 a	16 a	88 a
0.6	4,830 b	466 b	34 b	24 a	96 b
1.2	4,275 b	460 b	35 b	19 a	97 b
1.8	4,272 b	466 b	33 b	21 a	96 b
Ogle inoculated					
0.0	4,065 a	412 a	29 a	27 a	83 a
0.6	4,105 a	410 a	29 a	28 a	86 a
1.2	4,142 ab	395 a	27 a	31 a	90 b
1.8	4,991 b	419 a	30 a	34 a	93 b
Ogle noninoculated					
0.0	4,158 a	414 a	30 a	35 a	95 b
0.6	4,674 a	419 a	31 a	31 a	99 a
1.2	4,549 a	409 a	29 a	32 a	100 a
1.8	4,853 a	398 a	29 a	35 a	99 a

[z] Within groupings and within columns, means with the same letter are not significantly different at $P = 0.05$.

significantly reduced in the nontreated plots both with and without inoculation.

1993 study. As in 1992, all three rates of imidacloprid reduced disease incidence of BYD on Don when inoculated with viruliferous aphids, compared to the nontreated control plots (Table 1). In plots of Don inoculated with BYDV-PAV-IL, disease incidence was reduced from 60% in nontreated plots to 21% in plots treated with the highest rate of the insecticide (Table 1). In plots inoculated with BYDV-PAV-IL, up to 53% of the leaf samples harvested at random tested positive for BYDV-PAV-IL in TAS-ELISA (Table 3). A maximum of 5% of the leaf samples harvested at random from noninoculated plots showed virus titer when assayed by TAS-ELISA.

In 1993, as in 1992, insecticide treatments of both cultivars produced higher yields than the nontreated plots: inoculated and treated plots of Don yielded on average 24% more than the yield of the nontreated plots, and inoculated and treated plots of Ogle yielded on average 12% more than nontreated plots (Table 4). Plots of Don treated with 1.8 g a.i. kg^{-1} of seeds yielded 35% more than the nontreated plots. Although all plots were subjected to more severe heat and drought stress in 1993 than in 1992, noninoculated treated plots of Don yielded on average 16% more than plots not treated with insecticide.

In general, BYDV reduced test weight more in nontreated plots than in treated plots, and the highest rate of insecticide produced the highest test weight (Table 4). In plots of Don inoculated with BYDV, insecticide treatment significantly increased kernel weight, and seeds $tiller^{-1}$ was higher in plots treated with the highest rate of insecticide.

II. Wheat experiments (1993 and 1994). The data were combined over years. All comparisons of treatment means for the cultivar × rate combinations within a fixed level of inoculation are based on a probability level of 0.05.

Table 3. Percentage of flag-2 leaves of two oat cultivars, Don and Ogle, showing positive for the presence of barley yellow dwarf virus (BYDV)-PAV-IL by TAS-ELISA for the 1993 testing season[z]

Imidacloprid	Cultivars	
(g a.i. kg^{-1})	Don (%)	Ogle (%)
Inoculated		
0.0	45	53
0.6	33	35
1.2	30	35
1.8	30	13
Noninoculated		
0.0	0	5
0.6	0	0
1.2	0	5
1.8	0	0

[z] Forty leaves per treatment per variety were assayed by TAS-ELISA.

Disease incidence was higher in inoculated plots (Table 5). Plots that had not been inoculated with BYDV-PAV-IL exhibited some BYD symptoms, indicating that natural infection had occurred. In plots of Pioneer 2510 and Pacer inoculated with BYDV-PAV-IL and treated with the highest rate of the insecticide, disease incidence was 36 and 33% lower than in nontreated plots (Table 5). Based on TAS-ELISA, up to an average of 95% of the flag-2 leaves harvested at random from inoculated plots were positive for BYDV-PAV-IL; whereas an average of 7% of the flag-2 leaves from noninoculated plots were positive for virus (Table 6).

Grain yield was lower for all four cultivars in inoculated plots than in noninoculated plots, but all insecticide-treated plots yielded more than their nontreated counterparts. Treated noninoculated plots of Cardinal yielded, on average, 16% more than nontreated plots (Table 7). The yield increases due to insecticide treatment ranged from 15% in inoculated plots of Pioneer 2510 to 21% in inoculated plots of Clark.

In noninoculated plots of Cardinal and Clark, insecticide treatments also increased test weight significantly (Table 7). In general, kernel weight was lower in inoculated plots than in noninoculated plots, and was significantly lower in nontreated noninoculated plots of Pioneer 2510 and Clark than in plots treated with the highest rate of insecticide.

Except for noninoculated Clark, no significant differences were observed in the number of tillers m^{-2} among any of the treatments (Table 7). Insecticide treatments did increase the number of seeds $tiller^{-1}$ in inoculated plots of Pioneer 2510 and in noninoculated plots of Cardinal. Although not all cultivars differed in seeds $tiller^{-1}$ between nontreated and treated plots, all cultivars responded to BYDV infection in a similar way; inoculated plots always had fewer seeds $tiller^{-1}$ than their noninocu-

Table 4. Effects of imidacloprid on yield, test weight, yield components, and height of the BYDV-susceptible oat cultivar Don and the BYDV-tolerant oat cultivar Ogle for the 1993 testing season

Rate (g a.i. kg^{-1})	Yield (kg ha^{-1})	Test wt. (kg m^{-3})	Kernel wt. (g $1,000^{-1}$)	Seeds $tiller^{-1}$ (calc.)	Height (cm)
Don inoculated					
0.0	1,916 a[z]	392 a	32 a	9 a	61 a
0.6	2,286 b	403 b	35 b	9 a	64 a
1.2	2,286 b	402 b	35 b	9 a	62 a
1.8	2,579 b	401 b	36 b	11 b	62 a
Don noninoculated					
0.0	2,540 a	394 a	35 ab	10 a	64 a
0.6	2,940 b	391 a	33 a	13 b	64 a
1.2	2,705 ab	394 a	36 ab	10 a	61 a
1.8	3,210 c	400 b	36 b	12 ab	64 a
Ogle inoculated					
0.0	2,355 a	392 a	33 a	10 a	60 a
0.6	2,528 ab	396 ab	34 a	11 a	62 a
1.2	2,565 ab	400 b	35 a	11 a	61 a
1.8	2,838 b	401 b	35 a	12 a	63 a
Ogle noninoculated					
0.0	2,957 a	387 a	34 a	12 a	64 a
0.6	2,995 a	391 ab	34 a	12 a	64 a
1.2	3,249 a	387 a	34 a	13 a	66 a
1.8	3,095 a	395 b	37 a	11 a	66 a

[z] Within groupings and within columns, means with the same letter are not significantly different at $P = 0.05$.

Table 5. Incidence of barley yellow dwarf virus (BYDV) for four wheat cultivars, Cardinal, Pioneer 2510, Clark, and Pacer, in 1993 and 1994 field plots based on percentage of leaves exhibiting yellowing or reddening

Imidacloprid	Cultivars			
(g a.i. kg^{-1})	Cardinal (%)	Pioneer 2510 (%)	Clark (%)	Pacer (%)
Inoculated				
0.0	30 a[z]	53 a	44 a	46 a
0.6	22 a	51 a	41 a	39 ab
1.2	24 a	46 ab	34 a	33 ab
1.8	18 a	34 b	34 a	31 b
Noninoculated				
0.0	5 a	5 a	10 a	6 a
0.6	2 a	3 a	11 a	5 a
1.2	3 a	3 a	7 a	3 a
1.8	5 a	4 a	4 a	4 a

[z] Within groupings and within columns, means with the same letter are not significantly different at $P = 0.05$.

lated counterparts. The average number of seeds tiller^{-1} was 22 for the noninoculated plots and 18 for inoculated plots.

DISCUSSION

I. Oat experiments (1992 and 1993). Plots inoculated with viruliferous aphids had higher disease incidence and symptom expression than noninoculated plots. Plots that were not inoculated became infected naturally by aphids migrating throughout the season, but symptom expression in these plots remained lower than in the inoculated plots. This indicates that either few aphids were able to infect the plants or infection occurred at a later growth stage. Oats inoculated at a late Zadoks growth stage are not as likely to show as much symptom expression as oats inoculated at Zadoks growth stage 12 or 13 (23). In agreement with published results (3), we found that disease expression was consistently lower in the tolerant cultivar Ogle than in the susceptible cultivar Don.

High aphid densities were always detected in the control plots but rarely in plots treated with insecticide (data not shown). Gourmet et al. (15), studying the effect of imidacloprid on nonflight movement of *R. padi* and subsequent BYDV spread, observed that the insecticide's neurotoxicity incapacitated the aphids, causing them to walk atypically and often drop off plants if the leaves were tapped lightly. We suspect that the aphids were prone to fall off the plants in a field situation, due to movement of the plants in the wind, and were not able to recolonize the plants, thus preventing subsequent spread of the virus.

In 1992, seeding was normal, while in 1993, rain delayed seeding until 20 April, and a long period of drought followed, adding additional stress to the plants. Thus, vigor and yield potential was much higher in 1992 than in 1993. Yields were lower in 1993 than in 1992 in all plots for both cultivars. Even without inoculation, both cultivars were shorter in 1993 than in 1992. In 1993, plants showed stunting and reduced tillering due to environmental stress but much less leaf discoloration than in 1992. However, BYDV-PAV-IL was detected in 1993 using TAS-ELISA. We believe that high temperatures 2 to 3 weeks after inoculation and later in the growing season reduced plant vigor and probably reduced symptoms attributed to BYDV in 1993 compared to 1992. Only 5% of the leaf samples harvested at random from noninoculated plots in 1993 had detectable virus when assayed by TAS-ELISA. Again, heat and drought were major causes of lower yield in 1993.

In 1992 (a year of more typical weather), the cultivars differed in their response to infection: yield was more severely reduced for Don than for Ogle. The yield differences between inoculated and noninoculated plots were larger for Don than for Ogle. A difference of up to 2,260 kg ha^{-1} was observed in Don, while the largest difference detected in Ogle was 569 kg ha^{-1}. These differences were observed in plots treated with 0.6 g a.i. kg^{-1} seeds.

For the cultivar Don, only nontreated plots without inoculation had a significantly reduced test weight and kernel weight. BYDV infection has been reported to reduce test weight and kernel weight (8,32), an effect we failed to observe in our experiments. BYDV infection has been reported to reduce tillering in oat (22); but in our experiments, we observed no significant difference among treatments for either cultivar. In agreement with our findings, Thirakhupt and Araya (34) and Potter (26) did not find that cereal aphids

Table 6. Percentage of flag-2 leaves of four wheat cultivars, Cardinal, Pioneer 2510, Clark, and Pacer, showing positive for the presence of barley yellow dwarf virus (BYDV)-PAV-IL by TAS-ELISA combined over 1993 and 1994[z]

Imidacloprid	Cultivars			
(g a.i. kg^{-1})	Cardinal (%)	Pioneer 2510 (%)	Clark (%)	Pacer (%)
Inoculated				
0.0	94	95	88	81
0.6	89	86	88	76
1.2	80	85	84	93
1.8	75	80	68	74
Noninoculated				
0.0	19	11	14	13
0.6	5	5	5	5
1.2	4	5	1	0
1.8	1	8	8	3

[z] Eighty leaves per treatment per variety were assayed by TAS-ELISA.

Table 7. Effects of imidacloprid on yield, test weight, kernel weight, tillers, seeds tiller^{-1}, and height of the wheat cultivars Cardinal, Pioneer 2510, Clark, and Pacer combined over 1993 and 1994

Rate (g a.i. kg^{-1})	Yield (kg ha^{-1})	Test wt. (kg m^{-3})	Kernel wt. (g 1,000^{-1})	Tillers (m^{-2})	Seeds tiller^{-1} (calc.)	Height (cm^2)
Cardinal inoculated						
0.0	4,696 a[z]	561 a	32 ab	804 a	19 a	87 a
0.6	4,591 a	558 a	33 a	773 a	19 a	87 a
1.2	4,494 a	557 a	31 b	854 a	18 a	86 a
1.8	4,812 a	562 a	31 b	851 a	19 a	88 a
Cardinal noninoculated						
0.0	5,032 a	552 a	37 a	702 a	20 a	100 a
0.6	5,711 b	559 ab	38 a	676 a	23 b	102 a
1.2	5,836 b	562 b	34 b	740 a	24 b	98 a
1.8	5,954 b	561 b	34 b	788 a	23 b	97 a
Pioneer 2510 inoculated						
0.0	4,225 a	560 a	30 a	792 a	18 a	73 a
0.6	4,457 ab	550 b	31 a	884 a	17 a	74 a
1.2	4,602 ab	555 ab	30 a	809 a	20 ab	77 a
1.8	4,846 b	559 a	31 a	745 a	22 b	75 a
Pioneer 2510 noninoculated						
0.0	5,540 a	557 a	32 a	775 a	23 a	86 a
0.6	6,076 ab	558 a	33 ab	812 a	23 a	87 a
1.2	6,216 b	561 a	33 ab	789 a	24 a	86 a
1.8	6,412 b	560 a	34 b	826 a	24 a	88 a
Clark inoculated						
0.0	3,595 b	551 a	32 a	740 a	16 a	79 a
0.6	4,327 a	550 a	32 a	729 a	19 a	80 a
1.2	4,466 a	553 a	33 a	745 a	19 a	82 a
1.8	4,342 a	552 a	33 a	748 a	18 a	83 a
Clark noninoculated						
0.0	4,622 a	547 a	34 a	693 a	20 ab	91 a
0.6	5,058 ab	553 ab	35 ab	689 a	22 b	93 a
1.2	5,201 ab	558 b	37 c	870 b	17 a	92 a
1.8	5,271 b	560 b	36 bc	745 ab	20 ab	93 a
Pacer inoculated						
0.0	3,659 a	557 a	28 a	993 a	14 a	81 a
0.6	4,035 ab	558 a	28 a	1,080 a	14 a	83 a
1.2	4,295 b	559 a	28 a	996 a	16 a	85 a
1.8	4,384 b	562 a	28 a	1,008 a	16 a	87 a
Pacer noninoculated						
0.0	5,457 a	556 a	29 a	898 a	21 a	94 a
0.6	5,975 ab	559 a	30 a	924 a	22 a	94 a
1.2	6,080 b	560 a	30 a	950 a	22 a	92 a
1.8	5,922 ab	562 a	30 a	921 a	22 a	93 a

[z] Within groupings and within columns, means with the same letter are not significantly different at $P = 0.05$.

and BYDV affected the number of tillers of cultivar Abe wheat. Potter (26), studying the effects of BYDV and powdery mildew in oats and barley with single and dual infections, reported an increase in the number of tillers per individual oat plant infected with BYDV only.

In both 1992 and 1993, yields in noninoculated nontreated plots of Don were lower than in noninoculated treated plots. No differences in yield were observed in similar plots of the BYDV-tolerant cultivar Ogle. This suggests that BYDV infection accounted for most of the reduction in yield in the BYDV-susceptible cultivar Don.

II. Wheat experiments (1993 and 1994). Despite having a high percentage of infected plants based on TAS-ELISA, symptom expression in wheat was more subtle than in oats. Leaf discoloration in wheat is not as pronounced as in barley or oats. Other symptoms such as stunting, reduced tillering, and floret sterility are better detected under controlled experimental conditions where no biological and climatic factors obscure genotypic differences. Moreover, winter wheat is planted in the fall and is subjected to additional environmental factors that can affect disease ratings; therefore, the observed percent disease incidence reported in Table 1 may be lower than the actual disease incidence present in the plots.

In both 1993 and 1994, the cultivars Cardinal, Pioneer 2510, Clark, and Pacer were evaluated for BYDV tolerance in hills grown at the Agronomy-Plant Pathology Research Farm of the University of Illinois at Urbana-Champaign. Based on the evaluation, none of the cultivars are tolerant to infection with BYDV. These cultivars have a BYDV rating of 5.0 to 7.0 on a rating scale of 0 to 9, where 0 is very tolerant and 9 is very sensitive (unpublished data). We confirmed that these cultivars suffer yield loss due to infection with BYDV-PAV-IL.

The disease incidence in noninoculated plots was greater for Clark than for the other three cultivars. Noninoculated plots may have been naturally infected by aphids at any time during the season. In these plots, symptom expression was much less than in plots inoculated with BYDV, suggesting that either few aphids were able to infect the plants or infection occurred at a later growth stage. The results from TAS-ELISA agree well with the average of 5% disease incidence based on visual symptoms; an average of 7% of the flag-2 leaves from noninoculated plots were infected, as determined by TAS-ELISA.

As expected, the lowest yield for all cultivars occurred in the nontreated inoculated plots, and the highest yield was observed in the noninoculated plots treated with insecticide. The cultivars differed somewhat in their response to infection: yield was more severely reduced for Pacer than for the other cultivars studied. Pacer yielded 33% less in nontreated inoculated plots than in nontreated plots without inoculation. Pioneer 2510 and Clark had similar responses, averaging 24 and 22% yield loss, respectively, in nontreated inoculated plots compared to nontreated noninoculated plots. Yield of Cardinal in inoculated plots was lower than in noninoculated plots, but the yield of the nontreated plots was not significantly different from the insecticide treatments. This decrease in yield is probably due to environmental variation in the experiment. Almost all insecticide-treated plots had higher yields than their nontreated counterparts. Comparing the plots treated with the highest rate of insecticide to the nontreated plots, yields of the remaining three cultivars were higher both with and without inoculation.

Yield components such as kernel weight and the calculated number of seeds tiller^{-1} were similar in their response to BYDV, but were cultivar-dependent. Test weight and seeds tiller^{-1} were lower in noninoculated nontreated plots of Cardinal and Clark than in treated plots, while only noninoculated nontreated plots of Pioneer 2510 and Clark had lower kernel weight than the treated plots. Infection with BYDV has been shown to reduce test weight and kernel weight in winter wheat (8,34); but in our test, the reduction in these characters was greater in the noninoculated plots.

The number of tillers m^{-2} and height were unaffected in any of the cultivars tested. There is no consensus in the published literature regarding the effect of BYDV infection on tillering and plant height. Thirakhupt and Araya (34) showed that BYDV-PAV-infected aphids feeding on the susceptible cultivar Abe did not produce a clear effect on the number of tillers. Yount et al. (36) and Nkongolo et al. (21) reported significant reduction in tillering, but BYDV did not reduce plant height of all cultivars tested in their experiments. In our experiments, no difference in plant height was observed among rates of insecticide, but all cultivars responded similarly to infection with BYDV, in that inoculated plots were shorter than noninoculated plots.

LITERATURE CITED

1. Almand, L. K., and Mullins, J. W. 1991. NTN 33893: A new insecticide for thrips/aphid/whitefly control. Pages 80-81 in: Proc. Beltwide Cotton Prod. Conf.
2. Bai, D., Lummis, S. C. R., Leicht, V., Breer, H., and Satelle, D. B. 1991. Actions of imidacloprid and related nitromethylenes on cholinergic receptors of an identified insect motor neurone. Pestic. Sci. 33:197-204.
3. Brown, C. M., and Jedlinski, H. 1983. Ogle spring oat. Crop Sci. 23:1012.
4. Brown, C. M., and Kolb, F. L. 1989. Registration of 'Don' Oat. Crop Sci. 29:1572-1573.
5. Burnett, P. A. 1984. Barley yellow dwarf. Pages 6-13 in: Barley Yellow Dwarf. Proc. Workshop, CIMMYT, Mexico City. Dec. 1983. P. A. Burnett, ed. CIMMYT, Mexico, D.F.
6. Burnett, P. A., and Mezzalama, M. 1990. The barley yellow dwarf screening program at CIMMYT. Pages 434-440 in: World Perspectives on Barley Yellow Dwarf. Proc. Int. Workshop, Udine, Italy, July 1987. P. A. Burnett, ed. CIMMYT, Mexico, D. F.
7. Carrigan, L. L., Ohm, H. W., Foster, J. E., and Patterson, F. L. 1981. Response of Winter Wheat Cultivars to Barley Yellow Dwarf Virus Infection. Crop Sci. 21:377-380.
8. Comeau, A. 1987. Effects of BYDV inoculations at various dates in oats, barley, wheat, rye and triticale. Phytoprotection 68:97-109.
9. Cooper, J. I., and Jones, A. T. 1983. Response of plants to viruses: Proposals for the use of terms. Phytopathology 73:127-128.
10. D'Arcy, C. J., Murphy, J. F., and Mizklasz, S. D. 1990. Murine monoclonal antibodies produced against two Illinois strains of barley yellow dwarf virus: Production and use for virus detection. Phytopathology 80:377-381.
11. Dewar, A. M., and Read, L. A. 1990. Evaluations of an insecticidal seed treatment, imidacloprid, for controlling aphids on sugar beet. Pages 721-726 in: Proc. 1990 Brighton Crop Prot. Conf. - Pest Dis.
12. Elbert, A., Overbeck, H., Iwaya, K., and Tsuboi, S. 1990. Imidacloprid, a novel systemic nitromethylene analogue insecticide for crop protection. Proc. 1990 Brighton Crop Prot. Conf. - Pest Dis. 21:21-28.
13. Fitzgerald, P. J., and Stoner, W. N. 1967. Barley yellow dwarf studies in wheat (*Triticum aestivum* L.). 1. Yield and quality of hard red winter wheat infected with barley yellow dwarf virus. Crop Sci. 7:337-341.
14. Gildow, F. E. 1987. Barley yellow dwarf virus-aphid vector interactions associated with virus transmission and vector specificity. Pages 111-122 in: World Perspectives on Barley Yellow Dwarf. Proc. Int. Workshop, Udine, Italy, July 1987. P. A. Burnett, ed. CIMMYT, Mexico, D.F.
15. Gourmet, C., Hewings, A. D., Kolb, F. L., and Smyth, C. A. 1994. Effect of imidacloprid on nonflight movement of *Rhopalosiphum padi* and the subsequent spread of barley yellow dwarf virus. Plant Dis. 78:1098-1101.
16. Hewings, A. D., and D'Arcy, C. J. 1986. Comparative characterization of two luteoviruses: Beet western yellows virus and barley yellow dwarf virus. Phytopathology 76:1270-1274.
17. Horrellou, A., and Evans, D. D. 1980. Control of barley yellow dwarf virus with permethrin on winter barley in France. Pages 9-15 in: Proc. 1979 Br. Crop Prot. Conf. - Pest Dis., 1979.
18. Kendall, D. A., Smith, B. D., Burchill, R. G., and Chinn, N. E. 1983. Comparison of insecticides in relation to application date for the control of barley yellow dwarf virus in winter barley. Ann. Appl. Biol. 100(Suppl.):22-23.
19. Kolb, F. L., Brown, C. M., and Hewings, A. D. 1991. Registration of seven spring oat germplasm lines tolerant to barley yellow dwarf virus. Crop Sci. 31:240-241.
20. Mann, B. P., Wratten, S. D., Poehling, M., and Borgermeister, C. 1991. The economics of reduced-rate insecticide applications to control aphids in winter wheat. Ann. Appl. Biol. 119:451-464.
21. Nkongolo, K. K., Comeau, A., and Saint-Pierre, C. A. 1993. Relationships between leaf chlorosis and certain agronomic traits in wheat, triticale and wheat-triticale lines infected with the barley yellow dwarf virus (BYDV). Can. J. Plant Sci. 73:1225-1231.
22. Oswald, J. W., and Houston, B. R. 1953. The yellow dwarf virus disease of cereal crops.

Phytopathology 43:128-136.
23. Panayotou, P. C. 1979. Effects of barley yellow dwarf on the vegetative growth of cereals. Plant Dis. Rep. 63:315-319.
24. Perrin, R. M., and Gibson, R. W. 1985. Control of some insect-borne plant viruses with the pyrethroid PP321 (Karate). Int. Pest Cont. Vol. 27, Nov./Dec., pp. 142-3+.
25. Pike, K. S., Reed, G. L., Graf, G. T., and Allison, D. 1993. Compatibility of imidacloprid with fungicides as a seed-treatment control of Russian wheat aphid (Homoptera: Aphididae) and effect on germination, growth, and yield of wheat and barley. J. Econ. Entomol. 86:586-593.
26. Potter, L. R. 1979. The effects of barley yellow dwarf virus and powdery mildew in oats and barley with single and dual infections. Ann. Appl. Biol. 94:11-17.
27. Potter, L. R. 1982. Interaction between barley yellow dwarf virus and rust in wheat, barley and oats, and the effect on grain quality and yield. Ann. Appl. Biol. 100:321-329.
28. Rochow, W. F. 1979. Field variants of barley yellow dwarf virus: Detection and fluctuation during twenty years. Phytopathology 69:655-660.
29. SAS Institute. 1986. SAS User's Guide: Statistics. SAS Institute, Cary, NC.
30. Schroeder, M. E., and Flattum, R. F. 1984. The mode of action and neurotoxic properties of the nitromethylene heterocycle insecticides. Pestic. Biochem. Physiol. 22:148-160.
31. Singh, R. P., Burnett, P. A., Albarran, M., and Rajaram, S. 1993. Bdv1: A gene for tolerance to barley yellow dwarf virus in bread wheats. Crop Sci. 33:231-234.
32. Sommerfeld, M. L., Gildow, F. E., and Frank, J. A. 1993. Effects of single and of double infections with *Helminthosporium avenae* and barley yellow dwarf virus on yield components of oats. Plant Dis. 77:741-744.
33. Steel, R. G. D., and Torrie, J. H. 1980. Procedures of Statistics: A Biometrical Approach. 2nd ed. McGraw-Hill, New York.
34. Thirakhupt, V., and Araya, J. E. 1991. Effects of cereal aphid feeding and barley yellow dwarf virus on 'Abe' wheat in the laboratory. J. Plant Dis. Prot. 99(4):420-425.
35. Waterhouse, P. M., Gildow, F. E., and Johnstone, G. R. 1988. Luteovirus group. No. 339 in: Descriptions of Plant Viruses. Commonw. Mycol. Inst./Assoc. Appl. Biol., Kew, England.
36. Yount, D. J., Martin, J. M., Carroll, T. W., and Zaske, S. K. 1985. Effects of barley yellow dwarf virus on growth and yield of small grains in Montana. Plant Dis. 69:487-491.
37. Zadoks, J. C., Chang, T. T., and Konzack, C. F. 1974. A decimal code for growth stages of cereals. Weed Res. 14:415-421.