Use of Imidacloprid and Newer Generation Synthetic Pyrethroids to Control the Spread of Barley Yellow Dwarf Luteovirus in Cereals

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ABSTRACT

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In seven field experiments with wheat and oats sown in autumn, insecticides were applied to control aphids and thereby diminish the spread of aphid-transmitted barley yellow dwarf luteovirus (BYDV). Disease progress was followed over time by enzyme-linked immunosorbent assay (ELISA) on leaf samples using antiserum specific to BYDV serotype PAV. Two foliar applications of either of two newer generation synthetic pyrethroid insecticides, alpha-cypermethrin or beta-cyfluthrin, sprayed before flag leaf emergence and at rates as low as 12.5 g a.i./ha, decreased spread of BYDV by up to 75% and increased grain yields by up to 41%. These pyrethroids were more effective in decreasing BYDV spread than foliar applications of pirimicarb (150 g a.i./ha) or dimethoate (320 g a.i./ha), two applications of which decreased BYDV spread by up to 45% and increased grain yield by up to 14%. Seed treatment with imidacloprid (70 g a.i./ha) delayed BYDV spread in wheat and oats for up to 6 weeks after plant emergence. When imidacloprid seed dressing was followed by two foliar sprays of alpha-cypermethrin, BYDV incidence was decreased by up to 88%, and grain yield was increased by up to 76%. The predominant colonizing aphid species was *Rhopalosiphum padi*. Dressing seed with imidacloprid and/or foliar applications of the synthetic pyrethroids markedly decreased the numbers of aphids. Numbers colonizing plants were mostly lower than 10 per tiller on nontreated plots, suggesting the grain yield increases resulting from insecticide application were due to control of BYDV rather than to decreased aphid feeding damage. To minimize BYDV-induced grain yield losses in autumn-sown cereals, protection by insecticides should be provided from soon after plant emergence until the twelfth week of plant growth.

Barley yellow dwarf virus (BYDV) consists of several obligately aphid-transmitted, phloem-limited luteoviruses (31). It is the most widespread and economically important virus disease of cereals worldwide and also infects a large number of other graminaceous species (27,28). In Australia, economically important yield losses occur in wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and oat (*Avena sativa*) crops and in perennial grass pastures, especially in agricultural areas that receive high rainfall (>500 mm per annum) (7,13,14,15,20,21,23,33,34).

Annual grasses, perennial grasses, and volunteer cereals play an important role in the epidemiology of BYDV, as they serve as reservoirs of infection for spread by aphids to cereal crops (18,21). In southeastern Australia, perennial grass pastures provide a "green bridge" for BYDV to survive the summer and are the most important virus reservoirs for later spread to cereals (15). The climate in the southwest of Australia differs in that, except along its southern coastline, it is truly Mediterranean with little summer rain in most years. Summers are hot and dry with insufficient rain to support perennial pastures. However, wild perennial grass species survive in isolated locations, particularly roadside ditches and edges of streams, and these act as BYDV reservoirs for subsequent spread of the virus to autumn-sown cereal crops. Aphid vectors of BYDV survive the summer period in the parthenogenetic state on these surviving wild perennial grasses (8,18,21,22). Cereal crops are sown following opening rains in late April or May (late autumn) and harvested in December. Flights of aphids coming from wild grasses introduce the virus to cereal crops soon after plant emergence. *Rhopalosiphum padi* (oat aphid) and *R. maidis* (corn aphid) are the most abundant aphid species colonizing cereals, and *R. insertum*, *R. rufiabdominalis,* and *Sitobion miscanthi* are also found (18,21,25). BYDV serotypes PAV, MAV, RPV, and RMV are present in cereals and grasses (18,21).

Application of insecticides to kill aphid vectors in cereals is the most important cultural control strategy for decreasing BYDV spread and minimizing the grain yield losses it causes (17,28,30). The critical time to control BYDV in cereal crops is in the early stages of their growth, especially before tillering, because infection at this time has the greatest impact on grain yield (26,33). At present in Australia, pirimicarb, dimethoate, and demeton-S-methyl are the only insecticides recommended for aphid and BYDV control in cereals (25). In Europe, foliar applications of two synthetic pyrethroids (cypermethrin and deltamethrin) are reported to provide economically viable control of BYDV and to be more effective than carbamate insecticides such as pirimicarb (3,20). Seed treatment insecticides can also be used to protect cereals from BYDV in their early growth stages. Seed treatment with imidacloprid, which belongs to a new type of insecticide (chloronicotinyl group), is used commercially to control luteoviruses in sugar beet in Europe (9,32) and has been reported to diminish spread of BYDV in cereals in field experiments in Europe (4,6,19) and glasshouse experiments in North America (12).

This paper reports seven field experiments that investigated the effectiveness of seed dressings of imidacloprid, and foliar applications of two newer generation synthetic pyrethroids (alpha-cypermethrin and beta-cyfluthrin), pirimicarb, dimethoate, and triazamate in controlling BYDV, and increasing grain yields in wheat and oats.

MATERIALS AND METHODS

Virus isolates and antisera. Western Australian BYDV isolates PAV-M1 and RPV-MT1 were maintained in oats cv. Esk, and isolates MAV-SP1 and RMV-AV1 were cultured in kikuyu (*Pennisetum clandestinum*) and paspalum (*Paspalum dilatatum*) grasses, respectively. These isolates were used as positive controls in enzyme-linked immunosorbent assay (ELISA). Polyclonal antisera specific to MAV, PAV, RPV, and RMV were supplied by R. J. Sward, Institute of Plant Sciences, Department of Food and Agriculture, Burnley, Victoria, Australia, or R. M. Lister, Department of Botany and Plant Pathology, Purdue University, Indiana.

ELISA. Sap was extracted from leaf samples (1 g/5 ml) in phosphate-buffered saline (10 mM potassium phosphate, 150 mM sodium chloride), pH 7.4, containing 5 ml of Tween 20 and 20 g of polyvinyl pyrrolidone per liter using a leaf press (Pollahne, Germany). The extracts were

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collected in labeled plastic blood sample tubes. The extracts were tested for BYDV presence by double antibody sandwich ELISA using paired wells in immunoplates, as described by Clark and Adams (5). Coating IgGs were diluted in carbonate buffer (pH 9.6). The substrate was *p*-nitrophenyl phosphate at 1.0 mg/ml in diethanolamine at 100 ml/liter, pH 9.8. Control sap samples of BYDV-infected and healthy plants were included on each microtiter plate. Absorbance (A_{405}) values were measured in a Titertek Multiskan plate reader (Flow Laboratories, Helsinki, Finland). Absorbance values greater than twice those of the healthy controls were regarded as positive.

Assessment of BYDV infection. Cereal plots were sampled at regular intervals during the growing season. Individual plants were selected at random for this, but a 0.5-m-wide zone around the edge of each plot was excluded from sampling. The top 10 cm of the newest fully opened leaf was taken. The number of plants sampled was decreased from 50 leaves per plot at the beginning of the growing season to 15 leaves per plot at final sampling. No sampling was done after anthesis had commenced, although BYDV spread did not stop then. The leaves were tested singly or grouped at appropriate levels (2 to 10 leaves per group) before being tested for BYDV by ELISA. Percent incidence was estimated from grouped sample results using the formula of Gibbs and Gower (10). Antiserum to serotype PAV was always used, but at final assessment antisera to RPV, MAV, and RMV were also included in all experiments except for 1, 2, and 3, which were not tested for RMV. Some of the MAV positives recorded may be due to serological cross-reaction between PAV and MAV (21), but in a few cases MAV was the only serotype detected. As no RMV was detected, there were no cross-reactions between RPV and RMV (21).

Aphid counts. Aphid incidence was observed routinely during sampling in all experiments. In experiments 6 and 7, the total number of aphids (alate, apterous, and nymphal) were counted on 10 tillers selected at random per plot. These counts were done 3 weeks after the first foliar application (experiment 6) and 4 weeks after the final foliar application (experiment 7).

General details of field experiments. For each field experiment, details of the year, site, plot size, plot replication, and sowing date are listed in Table 1. The sites were Agriculture Western Australian Research Stations at Manjimup and Mount Barker and a farmer's property at Borden (Fig. 1); the average annual rainfall is 980 mm (Manjimup), 670 mm (Mt. Barker), and 650 mm (Borden). Each year, the experiments were sown as soon as possible after the first heavy rains of the growing season. Randomized block designs were used. Plots were sown with a tyned coneseeder. Rows were 17.5 cm apart, and the seeding rate was 80 kg/ha. All foliar-applied insecticides were diluted with water at a rate of 100 liters/ha and applied by boom spray. For each experiment, details of insecticides used and dates of foliar applications are listed in Table 2. Plant height measurements were made at anthesis by measuring the height of 10 randomly selected plants per plot to the nearest 5 cm. To obtain grain yields, we harvested the middle portion of each plot after discarding at least 0.5 m around the plot edges. Herbage dry weights were measured by cutting out all plants in 10 randomly placed quadrats (0.5 × 0.2 m) in each plot. Cut herbage was then placed in drying ovens at 45°C for approximately 48 h before weighing. Shriveled grain was measured by passing a random sample of 10 g of grain per plot over a 2-mm slotted sieve. Grain with a width of less than 2 mm passed through the sieve and was recorded as shriveled. Grain size was measured by weighing a random sample of 500 grains from each plot. Protein contents (crude protein × 5.7) were determined in a 10-g sample of grain per plot using a combustion method described by AOAC (1) and expressed on a percent dry basis.

Statistical analyses. Analysis of variance was done using Genstat version 5.3.1 on all data obtained from the experiments. Percent data for BYDV infection was angular transformed before analysis.

Table 1. General details of the seven field experiments

Exp.	Year	Site	Cereal (cultivar)	Plot size (m)	No. of replications	Sowing date
1	1991	Manjimup	Wheat (Spear)	6.4 × 15	6	14 May
2	1992	Borden	Wheat (Corrigin)	4.2 × 25	5	15 May
3	1992	Mt. Barker	Wheat (Corrigin)	4.2 × 25	5	21 May
4	1993	Manjimup	Wheat (Spear)	4.2 × 15	4	12 May
5	1993	Manjimup	Oats (Dalyup)	4.2 × 15	4	12 May
6	1993	Mt. Barker	Wheat (Spear)	4.2 × 20	8	24 May
7	1994	Manjimup	Oats (Dalyup)	2.8 × 15	4	25 May

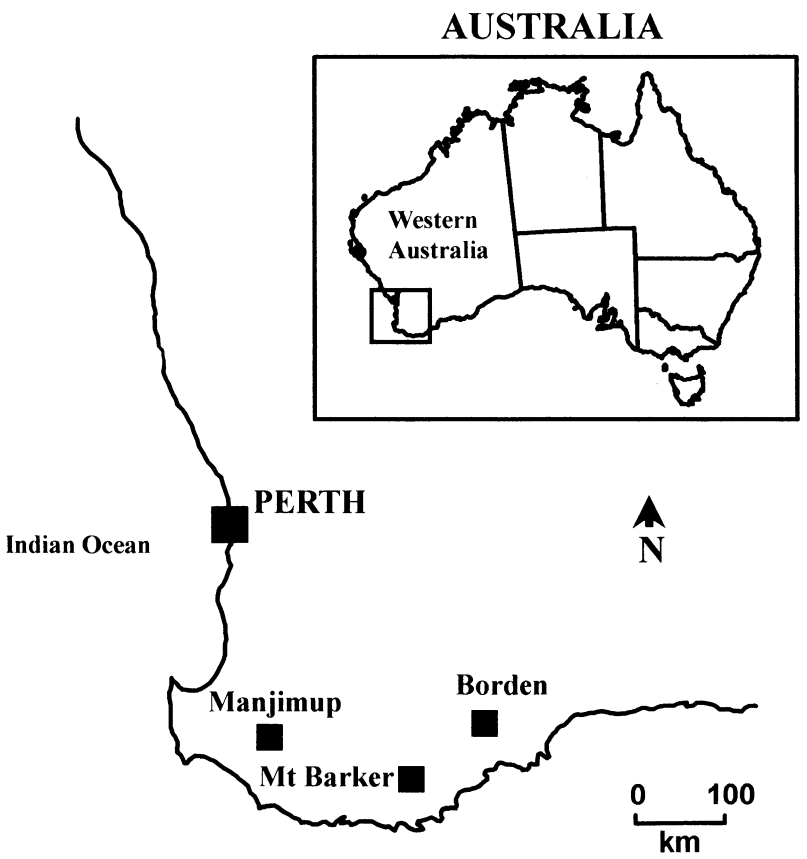

Fig. 1. Locations of experimental sites in southwest Western Australia.

RESULTS

Experiment 1. The only aphid found colonizing the wheat plants was *R. padi*. The first pirimicarb spray was applied when the average number of aphids on each main tiller reached five; it was never observed exceeding 10 per tiller in nontreated plots. By the final sampling

date (23 September), two foliar applications of pirimicarb had halved the amount of PAV detected in treated plots (Table 3). The level of PAV detected in final samples was two times that of RPV and three times that of MAV, RPV and MAV mostly occurring in mixed infection with PAV. Final infection levels in nontreated plots were 71% (PAV only) and 78% (overall BYDV). Application of pirimicarb was equally effective in decreasing the spread of all three serotypes. Grain yield was not significantly increased by spraying, but grain weight was increased by 6 to 8%.

Experiments 2 and 3. As in experiment 1, *R. padi* was the only aphid found colonizing the wheat plants. The first pirimicarb sprays were applied when the average number of aphids on each main tiller reached five; levels were never observed exceeding 10 per tiller. By the final sampling date (2 September) in experiment 2, significant decreases in PAV infection were obtained, even with the single-spray treatment; while in experiment 3, the two- and four-spray treatments both significantly diminished PAV's spread (Table 3). The level of PAV detected in final samples was three times the levels of RPV and MAV, RPV and MAV mostly occurring in mixed infection with PAV. In nontreated plots, the final levels of PAV were 37% (experiment 2) and 31% (experiment 3), while overall BYDV infection levels were 40% (experiment 2) and 31% (experiment 3). Application of pirimicarb was equally effective at decreasing the spread of all three serotypes. Grain yield was not significantly increased in pirimicarb-treated plots.

Experiment 4. *R. padi* was the only aphid species found colonizing the wheat plants, and its numbers were never observed exceeding five per tiller. The first prophylactic foliar spray treatments were applied 6 weeks after sowing and the second ones 6 weeks later. By the final sampling date, two applications of alpha-cypermethrin had decreased PAV spread by 80% (Table 4). This treatment was comparable in effectiveness to the combined imidacloprid seed dressing and three imidacloprid foliar sprays treatment, which diminished spread by 85%. In contrast, imidacloprid seed dressing used alone delayed PAV spread initially; but without later foliar sprays, infection levels subsequently increased to 38%, spread being diminished by 55%. Imidacloprid used as a foliar spray was less effective than used as a seed dressing. Foliar applications of triazamate did not significantly decrease virus spread. The level of PAV was three times that of RPV, but no MAV or RMV was found. RPV always occurred in mixed infection with PAV, and the final level of BYDV infection in nontreated plots was 85%. Application of insecticide was equally effective in decreasing spread of both serotypes.

When BYDV spread was decreased following insecticide application, the dry

Table 2. Details of insecticide and aphicide treatments used in each field experiment

Exp.	No. of applic.	Active ingredient	Insecticide	Manufacturer	Rate (g a.i./ha)	Dates of applic.
1	Nil					
	1	Pirimicarb	Pirimor	ICI	75	4 July
	2	Pirimicarb	Pirimor	ICI	150	4 July, 23 Aug
2	Nil					
	1	Pirimicarb	Pirimor	ICI	150	15 July
	2	Pirimicarb	Pirimor	ICI	150	15 July, 18 Aug
	4	Pirimicarb	Pirimor	ICI	150	16 June, 15 July, 4 Aug, 18 Aug
3	Nil					
	1	Pirimicarb	Pirimor	ICI	150	16 July
	2	Pirimicarb	Pirimor	ICI	150	16 July, 4 Sept
	4	Pirimicarb	Pirimor	ICI	150	17 June, 16 July, 19 Aug, 4 Sept
4, 5	Nil					
	2	Triazamate	Aztek	Cyanamid	50	21 June, 2 Aug
	2	Pirimicarb	Pirimor	ICI	150	21 June, 2 Aug
	2	Imidacloprid	Confidor	Bayer	70	21 June, 2 Aug
	1	Imidacloprid	Gaucho	Bayer	70	Seed dressing
	1	Imidacloprid	Gaucho +	Bayer	35	Seed dressing
	1		Confidor		70	2 Aug
	2	Alpha-cypermethrin	Fastac	Cyanamid	50	21 June, 2 Aug
	1	Imidacloprid	Gaucho +	Bayer	70	Seed dressing
	1		Confidor		70	2 Aug
	1	Imidacloprid	Gaucho +	Bayer	70	Seed dressing
	3		Confidor		70	21 June, 19 July, 23 Aug
6	Nil					
	2	Alpha-cypermethrin	Fastac	Cyanamid	25	20 July, 23 Aug
	1	Imidacloprid	Gaucho +	Bayer	70	Seed dressing
	2	Alpha-cypermethrin	Fastac	Cyanamid	25	20 July, 23 Aug
7	Nil					
	2	Alpha-cypermethrin	Fastac	Cyanamid	12.5	6 July, 15 Aug
	2	Alpha-cypermethrin	Fastac	Cyanamid	25	6 July, 15 Aug
	2	Alpha-cypermethrin	Fastac	Cyanamid	50	6 July, 15 Aug
	2	Beta-cyfluthrin	Bulldock	Bayer	6.25	6 July, 15 Aug
	2	Beta-cyfluthrin	Bulldock	Bayer	12.5	6 July, 15 Aug
	2	Beta-cyfluthrin	Bulldock	Bayer	25	6 July, 15 Aug
	2	Pirimicarb	Pirimor	ICI	150	6 July, 15 Aug
	2	Dimethoate	Sabouteur	Incitec Crop	320	6 July, 15 Aug
	1	Imidacloprid	Gaucho	Bayer	70	Seed dressing
	1	Imidacloprid	Gaucho +	Bayer	140	Seed dressing
	4	Alpha-cypermethrin	Fastac	Cyanamid	50	6 July, 15 Aug, 9 Sept, 11 Oct

Table 3. Effect of foliar applications of pirimicarb on barley yellow dwarf luteovirus (BYDV)-PAV spread in wheat and consequent effects on grain in experiments 1, 2, and 3

	Experiment 1			Experiment 2		Experiment 3	
Treatment	% BYDV infection[x]	Grain yield (kg/ha)	500 seed weight (g)	% BYDV infection[x]	Grain yield (kg/ha)	% BYDV infection[x]	Grain yield (kg/ha)[y]
Nil	71(59)	3,002	20.46	37(38)	2,092	31(34)	212
1 spray	63(53)	3,196	22.18	21(28)	2,211	26(30)	303
2 sprays	38(39)	3,220	21.69	13(21)	2,239	23(28)	338
4 sprays	...	...	...	10(19)	2,228	14(22)	409
P	0.001	ns[z]	0.01	<0.001	ns	<0.001	ns
sed	2.7		0.078	2.2		2. 1	
df	16		16	12		12	

[x] Data from final assessments (PAV serotype). Statistics shown are based on analysis of angular transformed data (in parentheses).
[y] Grain yields unusually low due to severe hail damage just before harvest.
[z] ns = not significant.

weight and height of plants were significantly increased at anthesis (Table 4). Alpha-cypermethrin, and imidacloprid used as foliar and seed treatments resulted in the greatest increases in both. Alpha-cypermethrin applied alone decreased BYDV levels enough to increase grain yields by 48%, while imidacloprid seed dressing followed by one to three imidacloprid foliar sprays decreased levels enough to increase yields by 23 to 34%. The decreased BYDV spread resulting from imidacloprid seed dressing followed by imidacloprid foliar sprays or foliar application of alpha-cypermethrin alone increased grain weight by 15 to 21%. Significantly decreased amounts of shriveled grain were found following pirimicarb, imidacloprid, and alpha-cypermethrin applications. No significant differences in protein contents of grain samples were found between any of the treatments.

Experiment 5. *R. padi* was the only aphid species found colonizing the oat plants, and numbers were never observed exceeding five per tiller. The timing of foliar spray treatments was as in experiment 4. Two foliar sprays of alpha-cypermethrin decreased PAV incidence by up to 57% (Table 5). This treatment was comparable in effectiveness with imidacloprid seed dressing followed by imidacloprid foliar sprays, which diminished spread by up to 52%. In contrast, imidacloprid seed dressing used alone delayed PAV spread initially, but without later foliar sprays infection subsequently increased. As a foliar spray, imidacloprid was as effective as when it was used as a seed dressing. Foliar applications of pirimicarb and triazamate did not significantly decrease PAV spread. The level of PAV was three times that of RPV, but no MAV or RMV was found. RPV always occurred in mixed infection with PAV, and the final level of BYDV infection in nontreated plots was 88%. Application of insecticides was equally effective at decreasing spread of both serotypes.

When BYDV spread was decreased following insecticide application, plant dry weight and height at anthesis increased significantly. The combined treatments of imidacloprid (seed dressing and foliar applied) and alpha-cypermethrin (foliar applied) produced the greatest plant dry weights and plant heights (Table 5). Seed dressing followed by foliar sprays, both of imidacloprid, increased yield by up to 88%. Alpha-cypermethrin alone increased yield by 71%, and imidacloprid seed dressing alone increased it by 62%. Foliar applications of triazamate, pirimicarb, or imidacloprid increased yield by up to 44%. The different insecticide treatments did not alter the proportion of shriveled grain.

Experiment 6. *R. padi* and a few *S. miscanthi* were found colonizing the wheat plants. The first prophylactic foliar spray treatments were applied approximately 8 weeks after sowing and the second ones 5 weeks later. PAV spread was significantly decreased by two foliar sprays of alpha-cypermethrin and by seed dressing with imidacloprid followed by foliar sprays of alpha-cypermethrin. At final sampling, the PAV infection levels in the nontreated, alpha-cypermethrin alone, and imidacloprid followed by foliar-applied alpha-cypermethrin treatments were 79, 19, and 13%, respectively, and all differed significantly ($P < 0.001$). The level of PAV was two times that of RPV, but no MAV or RMV was found. RPV always occurred in

Table 4. Effect of insecticide application on spread of barley yellow dwarf luteovirus (BYDV)-PAV in wheat and consequent effects on grain in experiment 4

Insecticide/aphicide	Rate (g a.i./ha)	% BYDV infection[z]	Whole plant dry weight (g)	Plant height (cm)	Grain yield (kg/ha)	500 seed weight (g)	Shriveled grain (%)
Nil		85(67) a	374.8 a	948 a	2,837 ab	15.95 a	8.7 ab
Triazamate	50	67(55) ab	384.4 ab	990 ab	2,771 a	16.67 a-c	7.4 a-c
Pirimicarb	150	41(40) cd	390.8 a-c	1,015 ab	2,987 a-c	16.95 a-d	6.2 cd
Imidacloprid (foliar spray)	70	52(46) bc	426.3 b-d	998 ab	3,211 a-e	16.27 ab	8.8 a
Imidacloprid (seed dressing)	70	38(38) cd	441.8 d	1,052 b	3,183 a-d	18.52 c-e	5.3 c-f
Imidacloprid (seed dressing + foliar spray)	35 70	24(29) de	444.5 d	1,050 b	3,745 d-f	17.82 a-e	5.5 c-e
Alpha-cypermethrin	50	17(24) e	452.1 d	1,052 b	4,204 f	18.67 de	3.8 ef
Imidacloprid (seed dressing + foliar spray)	70 70	22(28) de	467.2 d	1,055 b	3,811 d-f	19.35 e	3.0 f
Imidacloprid (seed dressing + foliar spray monthly)	70 70	13(21) e	480.5 d	1,032 b	3,492 a-f	18.35 c-e	5.2 c-f
P		<0.001	<0.001	0.002	0.005	0.011	<0.001
sed		6.5	23.47	38	353	0.934	1.14
df		24	24	24	24	24	18

[z] Data presented are for final assessment on 7 September. Statistics shown are based on analysis of angular transformed data (in parentheses).

Table 5. Effect of insecticide application on spread of barley yellow dwarf luteovirus (BYDV)-PAV in oats and consequent effects on grain in experiment 5

Insecticide/aphicide	Rate (g a.i./ha)	% BYDV infection[z]	Whole plant dry weight (g)	Plant height (cm)	Grain yield (kg/ha)	Shriveled grain (%)
Nil		88(69) a	347.1 a	710 a	2,996 a	4.7 bc
Triazamate	50	78(62) ab	379.1 ab	828 b	4,082 b	5.8 a-c
Pirimicarb	150	73(59) a-c	427.7 c	835 bc	4,307 b-d	7.1 a
Imidacloprid (foliar spray)	70	48(44) b-d	443.2 cd	860 b-d	4,288 bc	6.6 ab
Imidacloprid (seed dressing)	70	59(50) b-d	445.3 c-e	905 cd	4,868 b-e	4.2 c
Imidacloprid (seed dressing + foliar spray)	35 70	43(41) cd	481.8 d-f	920 d	5,149 c-e	5.1 bc
Alpha-cypermethrin	50	38(38) d	493.4 f	872 bc	5,112 c-e	5.4 a-c
Imidacloprid (seed dressing + foliar spray)	70 70	55(48) cd	502.9 fg	910 d	5,636 e	4.1 c
Imidacloprid (seed dressing + foliar spray monthly)	70 70	42(40) d	518.4 fg	930 d	5,337 e	3.9 c
P		0.017	<0.001	0.004	0.003	0.042
sed		8.85	21.64	34	379	0.83
df		24	24	24	16	8

[z] Data presented are for final assessment on 7 September. Statistics shown are based on analysis of angular transformed data (in parentheses).

mixed infection with PAV. The insecticide treatments were equally effective at decreasing spread of both serotypes. When aphids (*R. padi* and *S. miscanthi* combined) were counted 3 weeks after the first insecticide application (17 August), nontreated plots had an average of 22 aphids per tiller, but insecticide-treated plots had less than one per tiller.

The decrease in BYDV spread resulting from foliar application of alpha-cypermethrin alone increased grain yield by 41%, while dressing seed with imidacloprid followed by sprays of alpha-cypermethrin increased yield by 76%. Grain yields for the three treatments were 1,896, 2,680, and 3,334 kg/ha, respectively, for nontreated, alpha-cypermethrin alone, and combined imidacloprid seed dressing followed by sprays of alpha-cypermethrin ($P < 0.001$, sed = 217, df = 28).

Experiment 7. *R. padi* was the only aphid species found colonizing the oat plants, and its numbers were never observed exceeding 10 per tiller. The first prophylactic foliar sprays were applied 5 weeks after sowing and the second ones 5 weeks later. The synthetic pyrethroids alpha-cypermethrin and beta-cyfluthrin were significantly more effective at decreasing BYDV spread than either pirimicarb or dimethoate (Fig. 2, Table 6). Each insecticide decreased PAV spread by up to 87% (alpha-cypermethrin), up to 78% (beta-cyfluthrin), 45% (dimethoate), 28% (pirimicarb), and 17% (imidacloprid seed dressing). When applied at higher rates, alpha-cypermethrin or beta-cyfluthrin gave comparable decreases in PAV spread to those in the treatments with imidacloprid seed dressing followed by foliar sprays of alpha-cypermethrin. The level of PAV was three times that of RPV, but no MAV or RMV was found. RPV always occurred in mixed infection with PAV, and the final level of BYDV infection in nontreated plots was 60%. The different insecticides were equally effective against both serotypes.

There were no significant differences among the herbage dry weights for any of the treatments. However, plants were significantly taller in all insecticide-treated plots except those receiving imidacloprid seed dressing alone. The decrease in BYDV resulting from the insecticide treatment increased grain yield by up to 31% (combined treatment), 28% (alpha-cypermethrin), 31% (beta-cyfluthrin), 14% (dimethoate), and 5% (pirimicarb). Imidacloprid seed dressing was the only insecticide treatment that did not significantly decrease aphid numbers when counts were

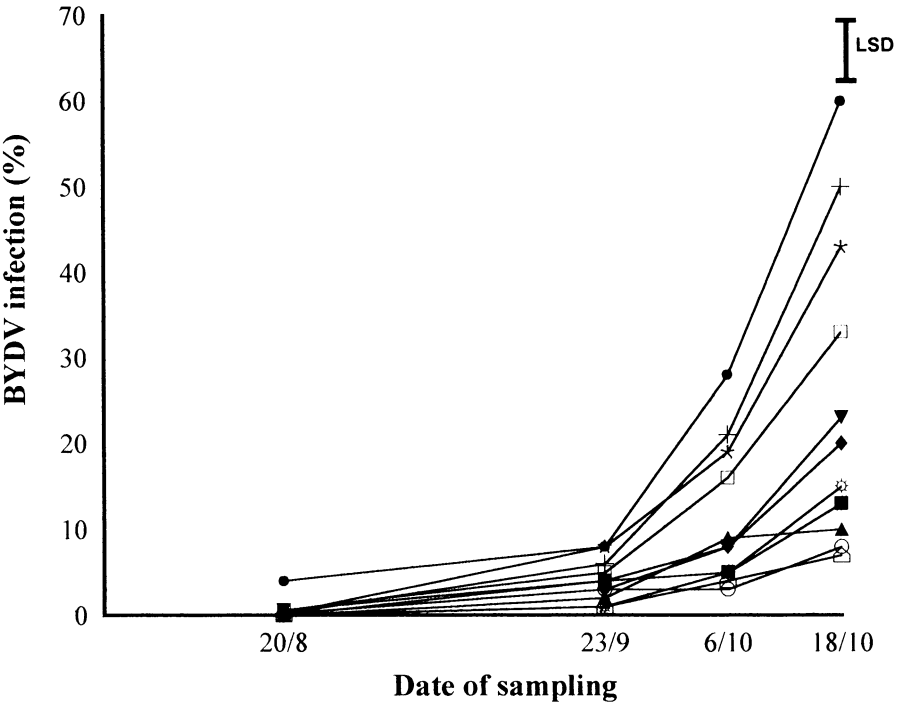

Fig. 2. Spread of barley yellow dwarf luteovirus (BYDV)-PAV in oats cv. Dalyup treated with different insecticides using seed dressing and foliar applications (experiment 7). Nil (●), imidacloprid seed dressing (70 g a.i./ha) (+), pirimicarb (150 g a.i./ha) (★), dimethoate (320 g a.i./ha) (□), alpha-cypermethrin (12.5 g a.i./ha) (◆), alpha-cypermethrin (25 g a.i./ha) (▲), alpha-cypermethrin (50 g a.i./ha) (○), beta-cyfluthrin (6.25 g a.i./ha) (▼), beta-cyfluthrin (12.5. g a.i./ha) (☼), beta-cyfluthrin (25 g a.i./ha) (■), and imidacloprid seed dressing (140 g a.i./ha) plus alpha-cypermethrin (50 g a.i./ha) (⌂). Percent infection data is back-transformed from angular transformed data ($P < 0.001$, LSD = 7).

Table 6. Effect of insecticide application on spread of barley yellow dwarf luteovirus (BYDV)-PAV in oats and consequent effects on grain in experiment 7

Insecticide/aphicide[x]	Rate (g a.i./ha)	% BYDV infection[y]	Mean no. aphids[z]	Whole plant dry wt. (g)	Plant height (cm)	Grain yield (kg/ha)	500 seed wt. (g)	Shriveled grain (%)
Nil		60(51) a	7.2 ab	2,356	78 ab	4,638 a	26.3 a-e	33 a
Dimethoate	320	33(35) d	1.1 c	2,426	81 b-d	5,280 a-c	26.2 a-f	42 c-g
Pirimicarb	150	43(41) c	0.9 c	2,332	80 a-c	4,879 ab	27.0 a	36 ab
Imidacloprid	70	50(45) b	8.7 a	2,404	77 a	4,638 a	25.7 a-g	37 a-c
Alpha-cypermethrin	12.5	20(27) ef	0.2 c	2,425	83 c-e	5,761 c-e	25.7 a-g	41 b-f
Alpha-cypermethrin	25	10(18) hi	0.2 c	2,403	82 c-e	5,921 c-e	26.2 a-f	40 b-e
Alpha-cypermethrin	50	8(17) i	0.4 c	2,417	80 a-c	5,708 c-e	26.4 a-d	42 c-g
Beta-cyfluthrin	6.25	23(29) e	0.03 c	2,364	82 c-e	5,476 b-e	24.4 g	47 g
Beta-cyfluthrin	12.5	15(22) g	0.4 c	2,431	81 bc	5,962 c-e	26.8 ab	43 d-g
Beta-cyfluthrin	25	13(21) gh	0.1 c	2,413	85 e	6,095 e	26.3 a-e	43 d-g
Imidacloprid + alpha-cypermethrin	70 25	13(21) gh	0.2 c	2,366	85 e	5,320 a-d	25.0 e-g	46 fg
Imidacloprid + alpha-cypermethrin	140 50	7(15) i	0.5 c	2,457	81 b-d	5,935 c-e	26.5 a-c	39 b-d
P		<0.001	<0.001	0.082	0.003	0.003	0.019	<0.001
sed		1.69	1.2	...	1.77	360	0.67	2.48
df		33	22	...	33	22	33	33

[x] Imidacloprid was applied as a seed dressing. All other insecticides applied as foliar sprays.
[y] Data are for final assessment on 6 September. Statistics shown are based on analysis of angular transformed data (in parentheses).
[z] Mean number of alatae, apterae, and nymphs on main tiller counted on 13 September.

done 4 weeks after the last insecticide application (13 September) (Table 6). Seed weight was not significantly increased or the proportion of shriveled grain decreased by the insecticide treatments.

DISCUSSION

To control aphids causing direct feeding damage, insecticides are usually applied at relatively late growth stages when aphid populations have reached or exceed threshold values of 10 to 15 aphids per tiller rather than being applied at early growth stages as in our experiments (25). At late growth stages, new infections with BYDV do not cause significant grain yield losses (26,32). Because of the low numbers of aphids found colonizing plants in these experiments (always <10 per tiller except in experiment 6) and the high levels of BYDV spread recorded, the grain yield losses found are attributed to BYDV infection rather than to aphid feeding damage.

Foliar application of newer generation synthetic pyrethroids alpha-cypermethrin and beta-cyfluthrin not only greatly decreased the spread of BYDV but also markedly increased grain yields of wheat and oats. These pyrethroids also increased plant dry weight and plant height, and in wheat increased grain weight and decreased the proportion of shriveled grain. Application rates of alpha-cypermethrin as low as 12.5 g a.i./ha were still effective. As the cultivars used in the experiments were sensitive (wheat cv. Spear and oats cv. Dalyup) or moderately sensitive (wheat cv. Corrigin) to BYDV infection (22), the magnitude of the yield losses would presumably have been smaller if BYDV-tolerant cultivars had been used. Cvs. Spear and Dalyup are currently widely sown in areas of Western Australia where BYDV is prevalent. The greater effect of BYDV infection in decreasing grain yield of cv. Dalyup in experiment 5 than of cv. Spear in experiment 4, which were adjacent experiments, may be due to somewhat greater sensitivity of the former to the virus. We do not know why BYDV control was rather less effective, however, in experiment 5 than in experiment 4. Possibly, penetration of foliage by insecticide was more extensive with wheat so that greater numbers of incoming viruliferous aphids landed on sprayed plots of oats, causing greater BYDV spread.

Our results with the application of newer pyrethroids in Australia resemble previous reports from Europe that older generation synthetic pyrethroids are more effective in decreasing BYDV spread than are pirimicarb and dimethoate (3,20). Application of the synthetic pyrethroids gave equivalent control of the BYDV serotypes PAV, MAV, and RPV. The effectiveness of these pyrethroids seems due to their antifeeding and repellent characteristics, which provide several weeks of protection to cereal crops (11,16). Pirimicarb is more specific to aphids than are pyrethroids and less damaging to their natural enemies, but it has a short persistence (30). Its poor performance in controlling BYDV spread may partly reflect the continual influx of aphid flights throughout winter in the southwest area of Western Australia. In winter cereals in cooler, temperate climates, flights normally cease after autumn and subsequently reappear when spring arrives (29). Triazamate, which is reported to be very effective against *Myzus persicae* (24), was less effective than pirimicarb in controlling the spread of BYDV.

Prophylactic insecticide sprays are necessary to control BYDV, as considerable spread often occurs within cereal crops by the time aphids are first seen by farmers. This is due to the difficulty of observing low aphid infestations early in the growing season. Our experiments indicate that spraying as early as possible after plant emergence is necessary if optimal BYDV control is to be achieved. This early application coincides with postemergence herbicide sprays, which can be tank mixed with the synthetic pyrethroids, further decreasing application costs. A second prophylactic spray 3 to 4 weeks after the first ensures adequate protection from BYDV through to flag leaf emergence.

Although Banks et al. (2) suggested that the use of insecticides to control BYDV in winter cereals in Australia is not economically feasible, in fact low rates of the two synthetic pyrethroids are very cost effective. The information obtained here on the impact of alpha-cypermethrin on BYDV and resulting grain yield increases in wheat and oats, and similar data for barley (S. J. McKirdy and R. A. C. Jones, *unpublished*), were used to do a benefit–cost analysis for its use in the BYDV-prone cereal-growing area of southwest Western Australia. The BYDV epidemic-affected area in an average year is approximately 200,000 ha (oats), 250,000 ha (wheat), and 200,000 ha (barley). If the whole epidemic-affected area were to be sprayed twice with alpha-cypermethrin in an average year, the yield increases would conservatively be 28, 25, and 20% for oats, wheat, and barley, respectively. The cost of two alpha-cypermethrin sprays at 12.5 g a.i./ha is A$6 × 2 = A$12 (US$9.2). The cost of spray application itself is A$8 × 2 = A$16 (US$12.3). Therefore, the cost of spraying is A$28 (US$21.5) overall. The average yields in tonnes/ha are 2.0 (oats), 1.6 (wheat), and 1.8 (barley). The current prices per tonne of oats, wheat, and barley are A$100 (US$76.8), A$160 (US$122.9), and A$140 (US$107.5), respectively. If we assume (1) that 70% of growers who spray receive full benefits from the spraying, while 30% merely break even as a result of spraying, and (2) we take into account the relative proportions of the overall oats, wheat, and barley areas involved, this gives a highly conservative figure for the average benefit per hectare of A$12 (US$9.2). Moreover, if the first spray is tank mixed with postemergence herbicides instead of being sprayed separately, the benefit becomes A$20 (US$15.4) per hectare. These dollar benefits, however, do not take into account the benefits arising from improved grain quality, as only the effects on grain yield are considered.

Different climatic scenarios (temperature, rainfall, and wind) have major impacts on populations of cereal aphids and consequently on BYDV spread. The effects of these climatic factors in determining aphid buildup and BYDV spread warrant investigation under the Mediterranean climatic conditions of southwest Western Australia, so that a comprehensive spray forecasting scheme (30) can be developed to predict when and if spraying is required in a given district in any particular year. However, summer rainfall and the timing of the "break of season" are good indicators of the likely BYDV severity within cereal crops. Thus, high summer rainfall and early opening rains favor development of BYDV epidemic years (e.g., 1993, experiments 4, 5, and 6). Conversely, dry summers and late opening rains in any particular region are not conducive to the development of BYDV epidemics (e.g., 1994).

When used as a seed treatment, imidacloprid offers an ecological advantage over foliar-applied synthetic pyrethroids, as it does not affect nontarget organisms (19). At a rate of 70 g a.i./ha, imidacloprid provided some control of BYDV spread in wheat and oats, delaying spread for up to 6 weeks. However, it was not effective for long enough to be used alone, so a foliar pyrethroid application approximately 6 weeks after emergence was also necessary. This result contrasts with those of Bluett and Birch (4), De Proft (6), and Knaust and Poehling (19) in Europe, who reported effective control of BYDV with imidacloprid seed dressing alone. This need for a follow-up spray with a pyrethroid presumably reflects the continuous barrage of viruliferous alate aphids landing on the crop throughout the critical first 12 weeks of growth in our experiments. Imidacloprid seed dressing (70 g a.i./ha) followed up by foliar sprays of alpha-cypermethrin (25 g a.i./ha) (experiment 6) gave excellent control of BYDV; lower rates of imidacloprid seed dressing (e.g., 35 g a.i./ha) followed by a foliar spray of pyrethroid at a rate below 12.5 g a.i./ha can effectively control BYDV spread; such a low-cost combined insecticide treatment would be a very attractive proposition for farmers. However, when imidacloprid was applied to foliage alone, it was less effective (experiments 4 and 5).

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