Irish Journal of Agricultural and Food Research **44:** 111–128, 2005

Grain yield reductions in spring barley due to barley yellow dwarf virus and aphid feeding

T.F. Kennedy† and J. Connery
Teagasc, Oak Park Research Centre, Carlow

The occurrence and control of barley yellow dwarf virus (BYDV) in spring barley was investigated, at Oak Park, in the periods 1990 to 1993 and 1996 to 2001. Barley was sown in March and April and treated with either organophosphorous or pyrethroid aphicide at various plant growth stages. The most common aphid encountered was *Sitobion avenae* and MAV the most common strain of BYDV. In untreated plots of March- and April-sown barley, 0.85% and 5.9%, respectively, of tillers had virus symptoms. Best control of symptoms, from a single aphicide in March- and April-sown crops, was a treatment at growth stage (g.s.) 14. This treatment contributed 77% of the reduction in symptoms recorded for multiple treatments in April-sown plots. The reduction in grain yield due to high, moderate and low BYDV infection in April-sown barley was 1.1 t/ha (20%), 0.65 t/ha (10%) and 0.36 t/ha (7%), respectively. In March-sown barley, pyrethroid aphicide applied at g.s. 14 significantly improved grain yield by 0.26 t/ha (4%). In the season having the most severe BYDV outbreak, a pyrethroid aphicide at g.s. 14 was best in controlling yield loss. Pyrethroid aphicide gave better control of symptoms and better yields than organophosphorous aphicide. The estimated yield reductions in untreated April-sown barley due to feeding damage by *Sitobion avenae* was 0.71 t/ha and 0.83 t/ha (10.6% and 11.3%) in the two seasons in which this aphid was plentiful. In the three seasons in which *Metopolophium dirhodum* was recorded the estimated yield reductions were 0.32 t/ha, 0.48 t/ha and 0.43 t/ha (5.2%, 5.6% and 5.7%).

Keywords: Aphicides; aphids; barley yellow dwarf virus; spring barley; yield loss

†Corresponding author: tkennedy@oakpark.teagasc.ie

Introduction

Barley yellow dwarf virus (BYDV) is an aphid-transmitted disease of cereals with widespread and worldwide occurrence (Plumb, 1983; Halbert and Voeglin, 1995; Lister and Ranieri, 1995). In addition to wheat, oats and barley the disease also infects maize and rye as well as many annual and perennial grasses totalling more than 150 species of the family *Poaceae* (D'Arcy, 1995).

BYDV is divided into two subgroups (Gill and Chong, 1979; Vincent, Lister and Larkins, 1991; Martin and D'Arcy, 1995) comprising various strains (Rochow, 1969; Gill, 1969; Plumb, 1974, 1995). MAV, PAV and SGV are placed in subgroup 1 and RPV and RMV in subgroup 2. MAV is the predominant strain found in Ireland (Kennedy and Connery, 2001 and unpublished observations).

Large yield reductions due to BYDV have been recorded for autumn-sown barley in Ireland and Europe (Barrett, Northwood and Horellou, 1981; Bayon and Ayrault, 1990; Kennedy and Connery, 2001). However, with exceptions that include Carver *et al.* (1999), Mann *et al.* (1997) and Edwards *et al.* (2001) there is little information on the effects of BYDV on grain yield in spring barley. Spring barley is the most common cereal grown in Ireland comprising over 50% of all cereals. In some seasons BYDV-like symptoms are found in crops particularly in those sown during April. The objective of this investigation was to quantify aphid and BYDV occurrence in barley sown in March and April together with an examination of control measures and effects on grain yield.

Materials and Methods

Experimental design

Spring barley was sown (157 kg/ha) in March and April at Kinsale, Co. Cork from 1990 to 1993, at Oak Park, Carlow from 1996 to 1999 and in April only at Oak Park in 2000 and 2001. There was an additional April sowing at Oak Park from 1991 to 1993 to give a total of 21 trials. March and April sowings were mostly during the third week of the month but ranged from 16 to 28 March and from 18 April to 3 May. The cultivars grown were Blenheim from 1990 to 1992, in 1996 and 1997 and at Oak Park in 1993, Aisling at Kinsale in 1993, Canasta in 1998 and Laird from 1999 to 2001. Crops received standard fertiliser, herbicide and fungicide treatments.

One or more applications of contact (pyrethroid) or systemic (organophosphorous) aphicide were applied to barley, for BYDV control, at various plant growth stages in the period to 1998. From 1999 to 2001 only contact aphicide was used. The contact aphicide used in 1990 to 1993 was fenvalerate (Sumicidin, 23 g active ingredient (a.i.)/ha) and esfenvalerate (Sumi-alpha 4.125 g a.i./ha) in 1996 to 2001. The systemic aphicide used in all trials was oxydemeton-methyl [Metasystox R (239 g a.i./ha) in 1990 to 1993 and Metasystox 250 (125 g a.i./ha) in 1997 to 1998]. Plant growth stages (g.s.) follow those described by Tottman, Makepeace and Broad (1979). In 1990 there were five treatments and an untreated control for each aphicide and each sowing date. These were: (1) g.s. 01; (2) g.s. 01 + 12; (3) g.s. 01 + 12 + 14; (4) g.s. 01 + 12 + 14 + 24; and (5) g.s. 01 + 12 + 14 + 24 + 31. The growth stages at which treatments were applied in the remaining trials are given in Table 1. Aphicide was applied with an azo-propane sprayer dispensing a volume of 337 l/ha. Treatments were arranged in randomised complete blocks. Fifteen of the 21 trials had six-fold replication and the remainder five-fold.

Plot size varied from 2.3 m × 20 m to 2.3 m × 30 m. Each plot was surrounded by a fallow strip 0.4 m wide.

Table 1. Plant growth stage at which contact systemic aphicides were applied to March and April-sown barley

Growth stage (g.s.) at which aphicide was applied	Year								
	1991[1]	1992[1]	1993[1]	1996[2]	1997[2]	1998[2]	1999[2]	2000[3]	2001[3]
					Contact aphicide				
2-leaf (g.s. 12)	✓	✓	✓	✓	✓	✓	✓	✓	
4-leaf (g.s. 14)	✓	✓	✓	✓	✓	✓	✓	✓	✓
First node (g.s. 31)	✓	✓	✓	✓	✓	✓	✓	✓	
g.s. 12 + 14	✓	✓	✓	✓	✓	✓	✓	✓	✓
g.s. 12 + 31	✓	✓	✓	✓	✓	✓	✓	✓	✓
Second node (g.s. 32)	✓	✓	✓	✓	✓	✓	✓	✓	
g.s. 12, 14, 24, 31	✓	✓	✓	✓	✓	✓	✓	✓	
Anthesis (g.s. 60)					✓	✓	✓	✓	✓
g.s. 14 + 60						✓			
g.s. 12, 14, 24, 31, 60						✓	✓	✓[4]	✓[4]
					Systemic aphicide				
g.s. 12	✓	✓	✓	✓	✓	✓			
g.s. 14	✓	✓	✓	✓	✓	✓			
g.s. 31	✓	✓	✓	✓	✓	✓			
g.s. 12 + 14	✓	✓	✓	✓	✓	✓			
g.s. 14 + 31		✓	✓	✓	✓	✓			
g.s. 32	✓	✓	✓	✓	✓	✓			
Untreated	✓	✓	✓	✓	✓	✓	✓	✓	✓

[1]Sown March and April at Kinsale and April only at Oak Park.
[2]Sown March and April at Oak Park.
[3]Sown April at Oak Park.
[4]Additional aphicide at g.s. 32.

Aphid sampling and identification

Aphid sampling was carried out using a vacuum insect net (D-vac, Dietrick, 1961), fitted with a 0.0929-m^2 sampling cone. Samples consisted of 20 sub-samples per plot, taken at random, and each of 15 s duration. From 1996 to 2001 the species and numbers of aphids on the ears and leaves of tillers, in selected treatments in April-sown barley, were recorded. Five tillers at each of five sampling locations per plot were examined. Aphids were identified using the keys of Stroyan (1952), Prior (1975) and Taylor *et al*. (1981).

Plant sampling

Plant measurements and sampling were carried out at locations along the longitudinal axis of plots and equidistances apart.

Virus testing

Leaf samples (10 to 15) were collected at five separate locations approximately 3 m apart in each plot at g.s. 41 to 43. Sap was extracted from 1 g of leaf sample and tested by DAS-ELISA (Clark and Adams, 1977) using F- and B-type antisera which detect MAV- and (PAV + RPV)-type virus (Plumb, 1974), respectively. Reagents were supplied by Bioreba AG (Switzerland). From 1996, leaf samples were screened for MAV and a 50:50 mixture of PAV- and RPV-type virus using TAS-ELISA (Adgen SAC, Scotland). Samples were considered positive when their spectrophotometer reading (405 nm) was three times greater than the mean value of negative controls.

Virus symptoms

The percentage of BYDV was determined by counting tillers with and without symptoms in each of four quadrats per plot. Symptoms were recorded at g.s. 43 to 49 using quadrats of 0.25 m^2.

Number of grains per ear
The number of grains per ear were counted from the aphicide treated and untreated plots in barley grown at Oak Park in 1993 and 1998 to 2001. Five sub-samples each of five adjacent ears were collected prior to harvest at intervals of 4 m.

Number of ears per metre
The ear density (expressed per m length of drill) in various treatments was recorded in 1993 and 1998 to 2001. Ear counts, per half metre drill length, were recorded at three locations per plot in 1993, at five locations in 1998 and 1999 and at six locations in 2000 and 2001.

Harvesting
Grain yield was recorded by harvesting entire plots using a specially modified combine harvester. Grain analyses (specific weight, percent screening (2.2-mm sieve) and 1000 grain weight) were carried out on a grain sample from each plot. Grain moisture was measured using a hot-air oven. Yields were expressed as t/ha at 15% moisture.

Yield reduction due to BYDV and aphid feeding
Where either BYDV or aphid feeding occurred separately, yield losses attributable to either were based on yield differences between treated and untreated plots. Where BYDV and aphid feeding occurred within the same trial yield reductions for each effect were estimated using the following considerations. Best control of BYDV and aphids together with maximum yields normally resulted from multiple aphicide applications between g.s. 12 and 60. Yield differences between sprayed and untreated plots were therefore due to both virus and aphid feeding. Best control of virus symptoms resulted from spraying plants at either g.s. 14 or g.s. 12 + 14. Yield improvements from the latter plots over those from untreated plots were attributed to virus. Differences in yield between multiple sprayed plots and those having best control of virus were attributed to aphid feeding.

Statistical analysis
Results were analysed using analysis of variance and correlation analysis. Differences among treatments were compared using least significant difference.

Results

Aphids
The number of aphids on April-sown barley, at g.s. 31, was 2.8-fold greater than for March-sown crops at the same stage of growth (Figure 1). In March-sown crops 68.3% of aphids were *Sitobion avenae*, 4.1% *Metopolophium dirhodum* and 27.6% 'others'; 20.1% were winged. The respective data for April-sown crops were 75.1% *S. avenae*, 20.2% *M. dirhodum,* 3.7% 'others'; 11.2% were winged. Of the winged aphids captured in March-sown crops, 64% were *S. avenae*, 7% *M. dirhodum* and 29% were 'others'. In April-sown crops, 97% of winged aphids were *S. avenae* and the remaining 3% were 'others'. Post-heading (g.s. 60) aphids were almost six-fold more numerous on April-sown than on March-sown barley. In five of the six April-sown trials in the period 1996 to 2001 aphid numbers increased between the vegetative stage (g.s. 14) and grain development (g.s. 70 to 80) (Table 2). No relationship was found between the number of aphids on plants at either g.s. 14 or 32 and those on tillers (leaves + ears) or on ears alone (g.s. 70 to 80).

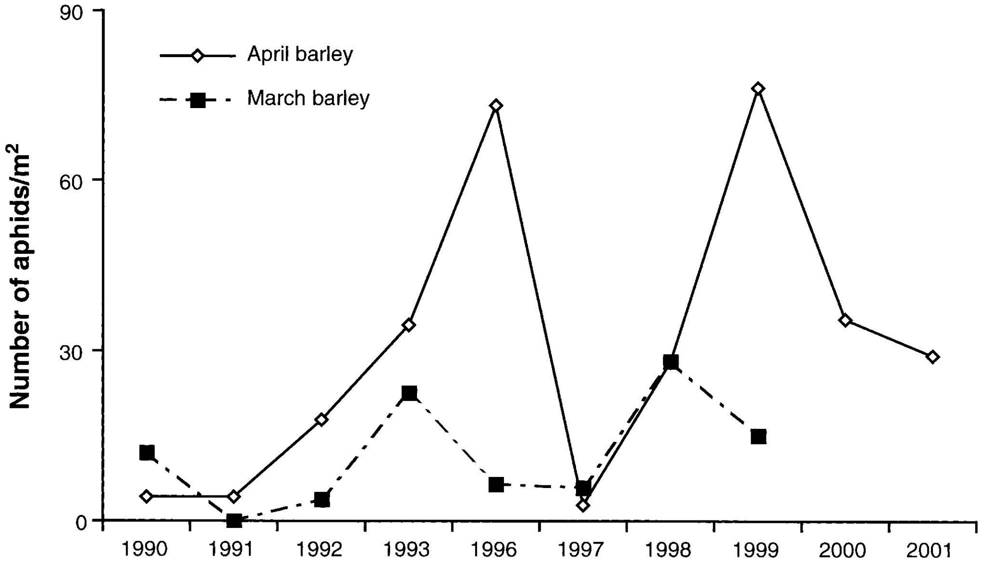

Figure 1: Number of aphids/m² at growth stage 31, in aphicide-untreated March- and April-sown barley.

The relative frequency distribution of aphids on tillers of April-sown barley on 1 July 1997 was 10, 2, 28, 36 and 24% *S. avenae,* respectively, on the ear and on the flag, second, third and fourth leaves. By 16 July the corresponding distribution was 77, 12, 9, 2 and 0%. The corresponding distribution of *M. dirhodum* on tillers on 1 July was 0, 0, 10, 17 and 73% while on 16 July the values were 0, 8, 44, 42 and 6%. The tiller distribution of *S. avenae* in early-July 1999 and mid-July 2000 was broadly similar to that for 1997. In mid-July 2001, 86% of aphids on tillers were *S. avenae*. Their relative distribution from the ear down to the fourth leaf was 49, 4, 9, 25 and 13%. The small number of *M. dirhodum* on plants in 2001 was approximately evenly distributed among the top four leaves.

A contact aphicide applied at g.s. 14 resulted in fewer aphids on tillers post-ear

Table 2. Average number of aphids (*S. avenae* and *M. dirhodum*) on tillers and percent of total on the ears of aphicide-untreated April-sown barley (1996–2001) and percent of total on ears

Time point	Year					
	1996	1997	1998	1999	2000	2001
Growth stage 14	0.01	<0.01	0.01	0.07	<0.01	<0.01
Growth stage 32	0.17	0.01	0.04	0.33	0.05	0.04
Growth stage 70 to 80	12.0 (59.0)[1]	19.2 (7.3)	<0.01 (100)	7.5 (8.1)	11.2 (14.4)	10.1 (37.3)
Percent S. avenae at growth stage 70 to 80	59.0	9.5	100.0	20.9	80.4	94.1

[1]( ) = Percentage of aphids on the ears.

emergence in four of the six April-sown trials in the period 1996 to 2001 (Table 3). Most of these aphids were *M. dirhodum.* Aphicide at either g.s. 31 (1997, 1998, 2000 and 2001) or 32 (1997, 2000) significantly reduced aphid numbers post ear emergence. However, spraying aphicide at five- (1999) and six-growth stages (2000 and 2001) between g.s. 12 and 60 did not prevent some aphid infestation of plants during growth stages 70 to 80. The effect of applying systemic and contact aphicide at g.s. 32 on aphid occurrence post ear emergence was compared only in 1997. Barley treated with either aphicide at g.s. 32 showed that the contact aphicide resulted in significantly ($P \leq 0.001$) fewer aphids per tiller at g.s. 65 to 70 than the systemic aphicide.

Virus symptoms

The BYDV symptoms described were those of the MAV-strain. The apical leaves of infected tillers were bright yellow in colour that extended backwards from the leaf tips. Distribution of symptoms throughout the crop was always random. Dwarfing of plants did not occur. Symptoms were visible from tillering until prior to ear emergence. Thereafter ears and awns masked symptoms. The presence of BYDV was serologically confirmed only in tillers having symptoms. The number of aphids on March-sown barley at g.s. 31 (D-vac samples) was correlated (r 0.88) with subsequent virus incidence. However, in the case of April-sown barley, there was no relationship between the number of aphids at g.s. 31 and virus incidence.

In the control plots of March-sown barley (8 trials) 0.85% (range 0.07–1.94%) of tillers had BYDV symptoms (Table 4). The mean infection in April-sown barley (13 trials) was 5.9% (range 0.1% to 36.4%; Table 5). The best control of symptoms by a single aphicide was from a contact aphicide at g.s. 14. Single aphicide treatment at g.s. 12, 31 or 32 were not as effective at controlling symptoms in either March- or April-sown barley (Figures 2 and 3). Plots receiving multiple contact-aphicide treatments had significantly fewer symptoms than plots sprayed at g.s. 14 in six of the 13 trials (Figure 3). However, 77% of the reduction in symptoms in multiple sprayed plots was provided by the single aphicide at g.s. 14. Comparing symptoms in plots (9 trials) treated with either systemic or contact aphicide at g.s. 12, 14, 12 + 14 and 14 + 31 showed that the plots treated with the contact aphicide had 15%, 32%, 44% and 22% fewer symptoms, respectively. These differences, however, were not significant. In the season of widespread BYDV (1993) the contact aphicide treatment resulted in

Table 3. Average number of aphids per tiller, post heading, on April-sown barley treated with contact aphicide at various growth stages and untreated barley (1996 to 2001)

Aphicide application at	Year					
	1996	1997	1998	1999	2000	2001
Growth stage 14	10.9		0.01	5.2	6.9	8.3
Growth stage 31		0.4	0.01		5.9	1.5
Growth stage 32		0.3	0.0		3.1	
Growth stage 12,14,24, 31,32,60				1.8[1]	1.5	0.2
Untreated	12.0	3.1	0.01	7.5	11.2	10.1
LSD (5%)		1.21		1.52	3.83	2.27

[1]Aphicide at growth stage 32 not included.

Table 4. Incidence of barley yellow dwarf virus (BYDV) and the yield increase relative to untreated barley, in March-sown barley treated with contact aphicide at growth stage (g.s.) 14, 12 + 14 and other growth stages

Year	Date sown	Tillers (%) with BYDV symptoms	Grain yield for untreated (t/ha)	Yield increase (t/ha) over untreated for aphicide treatment at				Maximum observed yield increase (t/ha)	
				g.s. 14		g.s. 12 + 14			
1990	22 March	1.23	6.67	–		0.34[a]	(0.28)[1]	0.82**[d]	(0.42)[1]
1991	28 March	0.07	6.47	0.08	(0.30)[1]	0.12	(0.20)	0.33[c]	(0.21)
1992	25 March	0.4	5.64	0.03	(0.75)	–0.06	(0.71)	0.36[b]	(0.53)
1993	24 March	1.94	6.71	0.26	(0.64)	0.31	(0.45)	0.31	(0.45)
1996	22 March	0.2	7.24	0.64	(0.34)	0.37	(0.44)	0.74[b]	(0.30)
1997	24 March	0.41	7.12	0.26	(0.54)	0.41	(0.25)	0.47[c]	(0.38)
1998	19 March	1.01	7.08	0.12	(0.07)	0.07	(0.09)	0.12	(0.07)
1999	16 March	1.47	7.23	0.39**	(0.14)	0.26**	(0.19)	0.56**[c]	(0.17)

[a]Treated at g.s. 01 + 12 +14.
[b]Treated at g.s. 14 + 31.
[c]Treated at g.s. 31.
[d]Treated at g.s. 12 + 14 + 24 + 31.
[1]( ) = s.e.

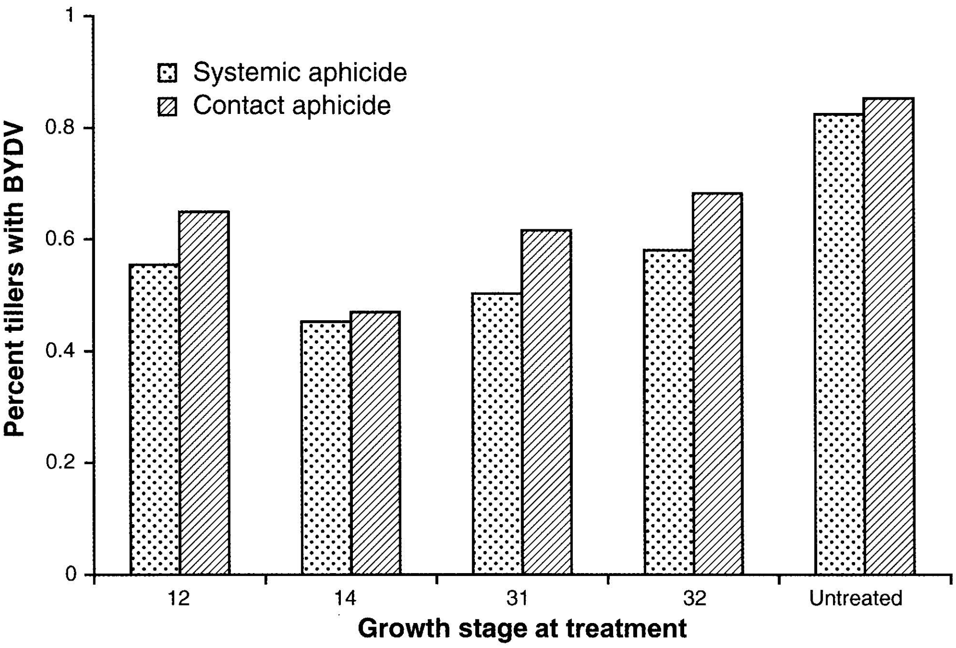

Figure 2: The percentage of tillers with barley yellow dwarf virus (BYDV) in March-sown barley sprayed at various growth stages with systemic (7 trials) and contact (8 trials) aphicide between 1991 and 2000.

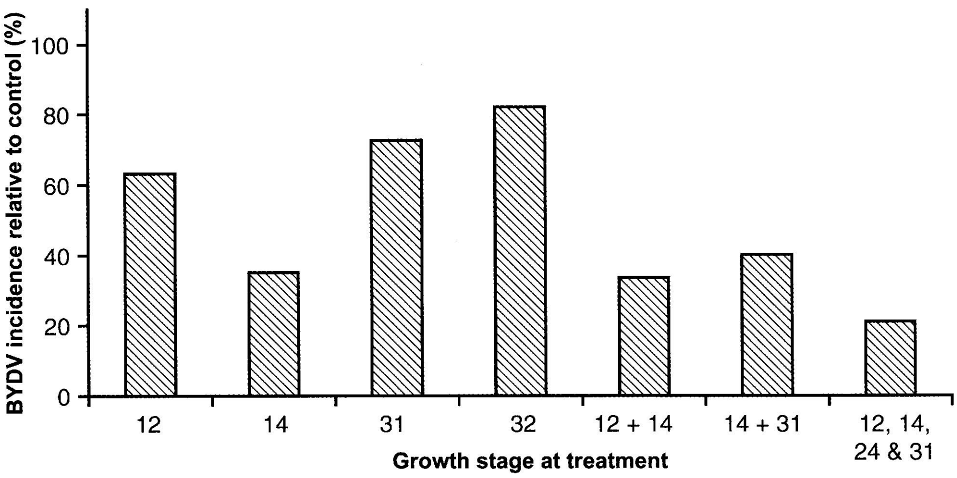

Figure 3: The percentage of tillers with barley yellow dwarf virus (BYDV) in April-sown barley sprayed with contact aphicide at various growth stages relative to untreated (100%) from 11 trials between 1991 and 2000.

significantly fewer virus symptoms than the systemic for comparisons at g.s. 14 ($P \leq 0.05$), g.s. 12 + 14 and 14 + 31 ($P < 0.1$).

Virus strains

From a total of 8047 leaf samples examined over the period 1990 to 1993 and 1996 to 2001, 4246 (52.8%) tested positive for F-type (MAV) virus. Of these 118 (1.5%) also tested positive for B-type (PAV + RPV) virus. March-sown barley had 42.3% of samples testing positive for F-type and 0.13% positive for B-type while in the April-sown barley 59.1% of samples were positive for F-type and 2.3% positive for B-type.

Ear and grain number

Treating April-sown barley with contact aphicide did not increase the number of ear-bearing tillers/m or grains/ear, relative to controls, for individual within-season comparisons. However, the combined data for aphicide applied at similar growth stages over the five seasons investigated showed that ear number was significantly increased relative to controls but grain number was not affected. For aphicides applied at g.s. 14, 14 + 31, multiple applications (at least 4) and controls the respective numbers of ears/m were 123.3, 120.5, 125.7 and 115.9 (LSD 5% = 6.91). The respective number of grains/ear were 22.3, 22.4, 22.4, and 22.4.

Grain quality

In March-sown barley treated with either contact (8 trials) or systemic aphicide (7 trials) bushel weight differed significantly from controls in only one trial. Again only one contact and one systemic March-sown trial had 1000-grain weight and percentage screenings significantly improved for treated relative to untreated plots. Of the 10 April-sown trials treated with systemic aphicide, bushel weight, 1000-grain weight and percentage screenings were significantly improved relative to controls in 7, 6 and 6 trials, respectively. In the 13 April-sown trials treated with contact aphicide these variables were significantly improved in 10, 9 and 9 trials, respectively.

Grain yield

Separate from BYDV considerations, grain yield for March-sown barley was significantly ($P \leq 0.05$) greater than that from April-sown crops. Comparing March-sown and April-sown crops on the same site in each of eight seasons showed the respective yields were 7.31 and 6.22 t/ha. For similar plots treated with systemic aphicide the yields were 7.11 and 5.59 t/ha, respectively.

March-sown barley

Yield of March-sown barley treated with contact aphicide at various growth stages compared with yield from untreated plots showed that in only 2 of the 8 trials investigated was there a limited number of treatments that differed by a significant amount (Table 4). The reduction in grain yield attributed to BYDV in March-sown trials was 0.27 t/ha (range 0.03–0.64). Data from 7 trials, for which comparisons are possible, showed that contact aphicide at g.s. 14 gave a significant ($P \leq 0.05$) yield improvement of 0.26 t/ha over controls. Furthermore, there was no yield advantage for applying a second or multiple sprays. Yields from plots sprayed at g.s. 12 were not significantly greater than controls. Plots treated with systemic aphicide did not significantly out-yield controls.

April-sown barley

The mean reductions in grain yield attributed to BYDV in high, moderate and low infected trials of April-sown barley were 1.1 t/ha (range 0.91–1.28), 0.65 t/ha (range 0.25–1.51) and 0.36 t/ha (range 0.14–0.82), respectively. However, the relationship between the percentage virus symptoms and yield reduction was poor (r 0.32). The maximum within-season yield difference between aphicide treated plots and controls ranged from 0.15 to 1.99 t/ha with a mean of 0.89 t/ha (Table 5). These yield increases were significant ($P < 0.05$) for various treatments (including those at g.s. 14 or 12 + 14) in 9 of 13 trials. In similar investigations with systemic aphicide the increase in plot yield over controls ranged from 0.17 to 1.05 t/ha with a mean of 0.49 t/ha. Six of the 10 trials treated with systemic aphicide had treatments with significantly ($P \leq 0.01$) higher yields than controls. Yield comparisons (9 trials) between contact and systemic aphicides applied at g.s. 12, 14 and 12 + 14, on April-sown barley showed a marginal but significant ($P \leq 0.1$) yield advantage for the contact aphicide. Combined results from 12 April-sown contact aphicide trials showed that plots receiving multiple sprays significantly ($P \leq 0.01$) out-yielded controls by 0.78 t/ha. Best yield improvement from applying a single aphicide was for treatment at g.s. 14 while in the case of two aphicide treatments those at g.s. 12 + 14 were best. The respective yield improvements of 0.39 and 0.56 t/ha were significantly ($P \leq 0.01$) greater than controls. In the season having the most severe BYDV outbreak (1993) the contact aphicide at g.s. 14 gave a yield improvement of 1.28 t/ha when compared with controls while the systemic aphicide at this growth stage only gave an increase of 0.67 t/ha. The addition of a second or multiple contact aphicide spray to that at g.s. 14 did not result in an increase in yield.

Estimates of reduction in grain yield due to aphid feeding damage, on April-sown barley, were made between 1996 and 2001. In 1996, g.s. 32 was the latest growth stage at which aphicide was applied and this treatment gave best control of aphids post ear emergence. The difference in yield between plots treated at g.s. 32 (highest treatment yield) and controls was 1.21 t/ha (18%). Best control of BYDV was achieved by applying aphicide at g.s. 12 + 14. The yield reduction in untreated plots compared with those sprayed at g.s. 12 + 14 was due to virus and was 0.5 t/ha (7.4%). The yield difference between plots sprayed at g.s. 12 + 14 and those sprayed at g.s. 32 was attributed to aphid feeding and was 0.71 t/ha (10.6%). BYDV infection was low in 1997. Plots treated with aphicide at g.s. 60, to prevent aphid feeding, had a similar amount of BYDV to controls. The yield reduction attributed to aphid feeding was 0.32 t/ha (5.2%). In 1999 the yield difference between plots receiving aphicide at five different growth stages and controls was 1.99 t/ha (23%). Of this 0.48 t/ha (5.6%) was attributed to aphid feeding and 1.51 t/ha (17.4%) due to virus. Similar calculations in 2000 showed a total yield reduction of 0.96 t/ha (12.7%) of which 0.43 t/ha (5.7%) was attributed to aphid feeding damage and 0.53 t/ha (7%) to BYDV. In 2001 the maximum reduction in yield was 1.56 t/ha (21.2%) of which 0.83 t/ha (11.3%) was attributed to aphid feeding and 0.73 t/ha (9.9%) to virus.

Discussion

Aphids

The aphids on spring barley were *S. avenae* and *M. dirhodum*. *S. avenae* was the dominant species in both March- and April-sown crops. Only in the case of one April-sown trial (1997) was *M. dirhodum* more plentiful than *S. avenae*. *S. avenae* and *M. dirhodum* also infest spring barley in Britain (Dean, 1973a,b; Jones, 1979; Mann *et al.,* 1997) where outbreaks of the latter species are associated with late-maturing crops (Dewar, Woiwood and de Janvrey, 1980). In Europe, *M. dirhodum* achieves high levels of infestation less

Table 5. Barley yellow dwarf virus (BYDV) incidence and the yield increase in barley treated with contact aphicide at g.s. 14, 12 + 14 and other growth stages (g.s.) relative to untreated April-sown barley

Year	Date sown	Tillers (% .) with BYDV symptoms	Grain yield for untreated (t/ha)	Yield increase (t/ha) over untreated for aphicide treatment at		Maximum observed yield increase (t/ha)
				g.s. 14	g.s. 12 + 14	
1990	23 April	13.45	5.04	– –	0.91**[a] (0.28)[3]	1.17**[d] (0.16)[3]
1991[1]	3 May	1.27	4.54	0.46** (0.21)[3]	0.83** (0.33)	0.84**[b] (0.32)
1991[2]	2 May	0.11	4.34	0.1 (0.35)	0.33 (0.34)	0.33 (0.34)
1992[1]	28 April	2.83	4.72	0.35** (0.08)	0.35** (0.11)	0.66**[b] (0.22)
1992[2]	4 May	1.27	5.09	0.11 (0.41)	0.38 (0.89)	0.72[b] (0.74)
1993[2]	26 April	36.39	4.02	1.28** (0.44)	1.21** (0.64)	1.28** (0.44)
1993[1]	28 April	1.01	4.24	0.05 (0.10)	0.15 (0.15)	0.15[b] (0.19)
1996	24 April	2.43	5.50	0.22 (0.21)	0.5** (0.29)	1.21**[g] (0.14)
1997	22 April	1.58	5.82	0.14* (0.11)	0.19** (0.11)	0.37**[g] (0.05)
1998	24 April	5.0	5.86	0.14 (0.23)	0.25 (0.23)	0.31[e] (0.14)
1999	14 April	4.93	6.66	1.34** (0.15)	1.51** (0.12)	1.99**[df] (0.09)
2000	18 April	3.5	6.61	0.53* (0.23)	0.43* (0.32)	0.96*[df] (0.43)
2001	23 April	2.9	5.81	0.16 (0.39)	0.73** (0.84)	1.56**[df] (0.30)

[1]Kinsale; [2]Oak Park; [3]() = s.e.
[a]Treated at g.s. 01 + 12 +14.
[b]Treated at g.s. 14 + 31.
[c]Treated at g.s. 31.
[d]Treated at g.s. 12+14 + 24+31.
[e]Treated at g.s. 12.
[f]Treated at g.s. 60.
[g]Treated at g.s. 32.

frequently than *S. avenae* (Dixon, 1987). *R. padi* was recorded only in 1999. In Germany, *R. padi* have been recorded feeding on the ears and leaves of spring barley (Kolbe, 1969) and this species is a particular problem of the crop in Sweden where spring barley is the main cereal crop grown (Wiktelius and Ekbom, 1985; Wiktelius, 1988). While spring barley is the most widespread cereal in Ireland, *R. padi* is not associated with the crop but is regularly found on early-sown winter barley (Kennedy and Connery, 2001).

The finding that the number of aphids on April-sown barley, at g.s. 31, was almost three-fold greater than for March-sown barley at this growth stage was not unexpected since aphid activity increases with the advancing season. Immigration of *S. avenae* and *M. dirhodum* into spring barley in Britain takes place during the second half of May (Dean, 1973a; Jones, 1979) by which time early sown crops are well developed and less likely to be infested than later sown crops. It might be expected that a large infestation at g.s. 31 would result in a greater infestation at later developmental stages. However, no relationship was found between the number of aphids on barley during the vegetative growth stage and at g.s. 70 to 80. Infestation levels at g.s. 70 to 80 are influenced by many factors. Aphid populations are positively influenced by mild winters (Dewar and Carter, 1984), high temperatures and low rainfall (Dean, 1974a; Jones, 1979; Pierre and Dedryver, 1984, 1985; Basedow, 1987; Plantegenest *et al.,* 1996), low occurrence of aphid-specific and polyphagous predators (Chambers and Sunderland, 1983; Dewar and Carter, 1984; Entwistle and Dixon, 1989; Sunderland *et al.,* 1987) and BYDV infection (Ajayi and Dewar, 1983). In the present study, the higher than normal number of *S. avenae* on the ears of barley in 1996 and 2001 coincided with below normal rainfall in April and July. *S. avenae* showed a strong preference for the apical leaves and were recorded on the ears in two of the six seasons investigated. The distribution of *S. avenae* was similar to that recorded for this species on winter wheat by Wratten (1978). *M. dirhodum* were predominantly found on the lower unsenesced leaves in 1997 but were more evenly distributed on leaves in 1999 and 2000. On wheat, *M. dirhodum* were found to feed on the lowest green leaves, moving to higher leaves as the lower leaves senesced (Wratten and Redhead, 1976; Wratten, 1978).

Effect of aphicides on aphids

Applying an aphicide at either g.s. 14, 31 or 32 resulted in fewer aphids per tiller post ear emergence compared with control plots. Approximately 80% of aphids were *M. dirhodum*. This result indicates that populations of *M. dirhodum* post ear emergence is determined to some extent by the aphid density during the vegetative phase of growth. However, the finding of aphids on tillers after g.s. 80 where plants had received 5 or 6 aphicide applications between g.s. 12 and 60 supports the view (Carter *et al.,* 1980) that aphid immigration occurs throughout the period of crop development. The finding of Mann *et al.* (1991) that a prophylactic aphicide just before g.s. 60 was often too early to prevent a later build up in *S. avenae* populations also indicates aphid immigration following this growth stage.

Virus symptoms

The percentage of plant tillers having BYDV symptoms in March-sown barley was 0.85% while that for April-sown barley was 5.9%. The higher incidence of disease in the late-sown crop, accords with other findings (Doodson and Saunders, 1970a,b; Edwards *et al.,* 2001), and corresponds with higher aphid numbers on plants as the season advanced. There were 2.8 times more aphids in the April-sown crop at g.s. 31 than in the March-sown crop at this growth stage. Despite the association between aphid numbers and levels of virus a relationship between aphid numbers at g.s. 31 and the subsequent level of virus infection was recorded only for March-sown barley. The absence of a relationship between these variables in April-sown barley indicates that alates are more important than apterous aphids in spreading the disease in late-spring sown crops. The almost 7-fold increased incidence of BYDV in April- relative to March-sown barley is greater than that recorded for March- and April-sown crops in Britain by Jenkyn and Plumb (1983).

Best control of symptoms in March-sown barley was achieved by applying aphicide at g.s. 14. However, the incidence of symptoms was low (0.85%) and a significant reduction was only achieved in 2 of the 8 trials investigated. Best control of symptoms by a single aphicide application in April-sown barley was again obtained by spraying at g.s. 14. Additional aphicide treatment gave a further significant reduction in symptoms in 6 of the 13 trials investigated. Overall, the reduction in symptoms in plots receiving multiple aphicide treatments showed that 77% of the reduction in symptoms was provided by the single aphicide at g.s. 14. In crops sown after mid-April there was a 60% chance (8 out of 13) of a moderate (>2% of tillers infected) BYDV infection occurring. Late-sown crops should therefore be treated with a single contact aphicide at g.s. 14, particularly if aphids are plentiful during this growth phase.

The control of BYDV in spring barley in England has been investigated by Jenkyn and Plumb (1983), Mann *et al.* (1997) and Carver *et al.* (1999). In general, these workers concluded that the use of aphicides for the control of BYDV in spring barley is not justified. Jenkyn and Plumb (1983) only encountered low to insignificant disease, and hence no response to insecticide, in their 4-year study. Investigations by Mann *et al.* (1997) found that spray treatments just prior to stem elongation were more effective in controlling aphids but that the benefits were short-lived. Their results, using pirimicarb insecticide, showed best control of virus in plots treated with insecticide 30 days following crop emergence. Thirty days post emergence of April-sown barley in Ireland would correspond to g.s. 31. Delaying aphicide application until g.s. 31 in this study was too late to obtain good control of BYDV. While Carver *et al.* (1999) found that the sequential application of two foliar insecticides was the most effective treatment in controlling BYDV in spring barley their results were inconsistent.

The pyrethroid insecticide fenvalerate/esfenvalerate was more effective than oxydemeton-methyl in reducing symptoms of disease in the present investigation. However, only in 1993, when BYDV was widespread, was there a significant difference in the control of symptoms between contact and systemic aphicide. Pyrethroids were also found by McKirdy and Jones (1996) to be more effective in decreasing the spread of BYDV in wheat and oats than either pirimicarb or dimethoate. Pyrethroid insecticide has also been found to give better control of aphid numbers in winter wheat than pirimicarb (Mann *et al.,* 1991).

Virus strain

The BYDV serotype encountered was almost completely the MAV-type. A small number (2.8%) of plant samples, testing positive for MAV, were also positive for a mixture of PAV- and RPV-type virus. In winter barley, in Ireland, MAV was the only strain found (Kennedy and Connery, 2001). The occurrence of MAV as the predominant strain is consistent with the occurrence of *S. avenae* and *M. dirhodum* which are effective transmitters of this strain (Rochow, 1970; Plumb, 1995). While the most efficient transmitter of PAV- and RPV-types is *R. padi* this aphid was only recorded in 1999 when a small number of plant samples were positive for these strains. PAV can also be transmitted by *S. avenae* and *M. dirhodum,* but at reduced efficiency, while RPV can be transmitted by *M. dirhodum* (Rochow, 1979, 1982; Plumb, 1995). Normally, *M. dirhodum* and *R. padi* over-winter on their respective primary hosts of *Rosa* and *Prunus* species (Stroyan, 1952; Dean, 1974b; Tatchell. Plumb and Carter, 1988). Aphid migrants arriving in cereal crops from their primary hosts in spring will not be transmitting BYDV. It is concluded, therefore, that the main vector of BYDV in spring is *S. avenae.*

Grain and ear number

The number of ears/m was greater in aphicide-treated than untreated plots. The number of grains/ear, however, was not increased by the use of aphicide. Reductions in grain and tiller number in spring cereals due to BYDV transmitted by *R. padi* have been recorded by Doodson and Saunders (1970a,b) and Sommerfeld, Gildow and Frank (1993). Investigations by these workers used either glasshouse or field micro-plots with BYDV other than the MAV-type virus. The control of the MAV-type BYDV by aphicides in autumn-sown barley at Oak Park was found to result in significantly more ears/m^2 and more grains/ear relative to untreated plots (Kennedy and Connery, 2001). The effects were greater for ear density than grain number. While the reduction in the number of tillers/m in spring barley by the MAV-type BYDV is consistent with that recorded for this strain in winter barley the effect was only significant for the combined data over several seasons.

Grain quality

Improvements in grain yield for aphicide-treated relative to untreated plots, particularly in April-sown barley, were correlated with increases in bushel and 1000-grain weights and reductions in percent screenings. This result is consistent with the finding that the MAV-strain of BYDV in winter barley prevents normal grain fill, thereby resulting in poor quality grain (Kennedy and Connery, 2001). Reductions in grain size corresponding with reductions in grain yield in spring barley due to BYDV transmitted by *R. padi* have been recorded by Doodson and Saunders (1970a,b) and Edwards *et al.* (2001) and due to feeding by *M. dirhodum* by Lee, Wratten and Kenyi (1981).

Grain yield

In only two of the eight March-sown trials did plots treated with contact aphicide have significantly greater yields than untreated plots. These trials took place in two of the three seasons in which BYDV was most plentiful. The small improvement in yield in March-sown aphicide-treated plots is not surprising since BYDV infection and aphid infestation in these crops were low. While the improved yield of 0.26 t/ha for applying aphicide to March-sown barley is relatively small, nevertheless, it is economically justifiable since aphicide is inexpensive and can be applied with herbicide. However, as already stated, significant yield increases were only obtained in 2 years and in four of the eight March-sown trials the mean level of infection was only 0.27% (of tillers with virus symptoms). In the majority of seasons in Ireland, BYDV in March-sown barley is not a major occurrence and therefore routine spraying is not justified.

The control of BYDV in April-sown barley gave significant yield improvements in 9 of the 13 trials. This suggests a 70% probability of infection in April-sown crops. Overall, aphicide at g.s. 12 + 14 gave best control of BYDV in terms of preventing yield loss due to the disease. Seventy percent of the yield loss prevented by the two sprays was contributed by the spray at g.s. 14. In seasons of severe BYDV outbreaks (e.g. 1993) the recorded yield reductions are considered to underestimate the effect of virus on yield. In 1993, a single aphicide at g.s. 14 prevented a yield reduction of 1.28 t/ha. The addition of an extra aphicide did not improve grain yield. The level of infection in plots treated at g.s. 14 was 8.6% compared with 36.4% in controls. In this study significant reductions in grain yield were recorded when greater than 1.5% of tillers had virus symptoms. For example, infections of 3%, 3.5% and 5% were associated with yield reductions of 0.73, 0.53 and 1.5 t/ha, respectively. This suggests that the reduction of 1.28 t/ha for an infection of 36% was underestimated by a considerable amount due to the residual infection in sprayed plots. The above results for spring barley concur with those of Ryden (1990) for control of BYDV in spring oats in Sweden. Ryden (1990) recorded a yield increase of 38% when plots were treated, with the pyrethroid insecticide fenvalerate, at an early growth stage. Investigations on April-sown barley in Britain (Mann *et al.,* 1997; Carver *et al.,* 1999) have not shown a major or predictable impact of BYDV on yield. While least virus infection and highest yields were recorded for plots treated with aphicide prior to stem extension by Mann *et al.* (1997) the relationship was not significant. In some April-sown trials, Carver *et al.* (1999), obtained significant yield increases by controlling BYDV with either one or two aphicide applications. However, their results were inconsistent and showed poor relationship between yield response and BYDV infection.

For growers of spring barley in Ireland there is the dilemma of whether or not to apply an aphicide to April-sown crops. The problem is the absence of an effective aphid-sampling method to warn of an impending BYDV outbreak. Sampling aphicide-untreated winter barley by means of a D-vac sampler does indicate the extent of aphid survival over the winter and the rate of multiplication in spring. This is a useful guide of possible virus occurrence. The most effective way of determining the threat to spring barley is to examine crops from the second leaf stage of growth. Since most infection in Ireland is due to winged *S. avenae*, immigration by these aphids can be detected by the finding of immature wingless aphids. Finding immatures indicates the activity of winged aphids, however, even in seasons of subsequently widespread BYDV, these aphids are not easily found on plants. The difficulty of finding aphids on plants, the absence of a BYDV forecast and the effect of virus on yield indicate that barley crops sown after mid-April in Ireland should be treated with contact aphicide at g.s. 14.

In general, the systemic aphicide oxydemeton-methyl was less effective in preventing yield reduction due to BYDV when compared with the contact pyrethroid aphicide, esfenvalerate.

Yield reductions due to aphid feeding

The estimated reductions in grain yield in this study due to feeding on plants by *S. avenae* were greater than those due to *M. dirhodum* and are in line with those for spring wheat (Wratten, 1975, 1978). Wratten (1975, 1978) found *S. avenae* caused a greater reduction in yield than *M. dirhodum* when densities of both species were similar. Wratten and Redhead (1976) suggest that yield losses caused by these two aphids are probably due to their feeding position on the plant with *S. avenae* feeding on the ears and *M. dirhodum* feeding on the leaves (Dean and Luuring, 1970; Dean, 1973a; Watt, 1979; Cannon, 1986). The occurrence of BYDV and aphid feeding damage on plants in the same trials makes it difficult to determine the extent by which either is reducing grain yield. As with BYDV, applying as many as five aphicides between g.s. 12 and 60 was unable to keep plants free of aphids during the grain development phase of growth. The reduction of 0.71 t/ha attributed to *S. avenae* in 1996 is an underestimate since it is based on the difference between aphicide untreated plots and those treated at g.s. 32, the latest growth stage at which aphicide was applied in 1996. An aphicide at g.s. 60 or later would have been more effective in preventing the build-up in *S. avenae* which occurred in late June and July 1996.

This investigation showed BYDV infection in March-sown barley never exceeded 2% (tillers with symptoms) nor did yield reduction due to virus exceed 0.7 t/ha. Aphid feeding on ears of March-sown barley was not observed. The findings show there is no justification for the prophylactic use of aphicides on March-sown barley in Ireland. Barley sown after mid-April has a high probability of becoming infected with BYDV. The percentage of tillers with disease can exceed 30% a yield reduction of the order of 1.3 t/ha is likely. Applying an aphicide at g.s. 14 gives good control of the disease and should be applied to crops sown after mid-April. While aphid feeding on the ears of April-sown barley occurs occasionally, treatment of crops with aphicide is only warranted when infestations increase during the grain filling and ripening phase of plant development.

Acknowledgements

The authors wish to thank T. Hegarty and Ms L. Kirwan, for statistical advice, L. Dowley and E. O'Sullivan for reading the manuscript and P. Sisk and J. McCarthy for assistance with the Cork sites.

References

Ajayi, O. and Dewar, A.M. 1983. The effect of barley yellow dwarf virus on field populations of the cereal aphids, *Sitobion avenae* and *Metopolophium dirhodum*. *Annals of Applied Biology* **103:** 1–11.

Barrett, D.W.A., Northwood, P.J. and Horellou, A. 1981. The influence of rate and timing of autumn applied pyrethroid and carbamate insecticide sprays on the control of barley yellow dwarf virus in English and French winter cereals. *Proceedings of the 1981 British Crop Protection Conference – Pests and Diseases*, pages 405–412.

Basedow, T. 1987. Die Reaktion von Getreideblattausen (Hom., Aphididae) bei holozyklischer Uberwinterung auf die Aussaatzeit von Weizen. Mit Beobachtungen zum Einfluss heftiger Niederschlage. *Anzeiger-fuer-Schaedlingskunde-Pflanzenschutz-Umweltschutz* **60**(7)**:** 127–133.

Bayon, F. and Ayrault, J.P. 1990. Barley yellow dwarf virus: losses, virus-plant relationships, chemical control of vectors. In: 'World Perspectives on Barley Yellow Dwarf' (ed. P.A. Burnett), CIMMYT Mexico, pages 471–472.

Cannon, R.J.C. 1986. Summer populations of the cereal aphid *Metopolophium dirhodum* (Walker) on winter wheat: three contrasting years. *Journal of Applied Ecology* **23:** 101–114.

Carter, N., McLean, I.F.G., Watt, A.D. and Dixon, A.F.G. 1980. Cereal aphids: a case study and review. *Applied Biology* **5:** 271–348.

Carver, M., Overthrow, R., Lucas, J. and Phillips, S. 1999. The importance of barley yellow dwarf virus (BYDV) infection in spring barley and opportunities to manage the disease. HGCA Project Report. No. 206, 19 pages.

Chambers, R.J. and Sunderland, K.D. 1983. The abundance and effectiveness of natural enemies of cereal aphids on two farms in southern England. In: 'Aphid Antagonists' (ed. R. Cavalloro). *Proceedings of a Meeting of the EC Experts' Group, Portici, Italy* (23–24 November, 1982), Balkema, Rotterdam, pages 83–87.

Clark, M.F. and Adams, A.N. 1977. Characteristics of the microplate method of enzyme-linked immunosorbent assay for the detection of plant viruses. *Journal of General Virology* **34:** 475–483.

D'Arcy, C.J. 1995. Symptomatology and host range of barley yellow dwarf. In: 'Barley Yellow Dwarf – 40 Years of Progress' (ed. C.J. D'Arcy and P.A.

Burnett), APS Press, St. Paul, Minnesota, pages 9–28.

Dean, G.J. 1973a. Distribution of aphids in spring cereals. *Journal of Applied Ecology* **10:** 447–462.

Dean, G.J. 1973b. Aphid colonization of spring cereals. *Annals of Applied Biology* **75:** 183–193.

Dean, G.J. 1974a. Effect of temperature on the cereal aphids *Metopolophium dirhodum* (Wlk.), *Rhopalosiphum padi* (L.) and *Macrosiphum avenae* (F.) (Hem., Aphididae). *Bulletin of Entomological Research* **63:** 401–409.

Dean, G.J. 1974b. The four dimensions of cereal aphids. *Proceedings of the Association of Applied Biologists, Annals of Applied Biology* **77:** 74–78.

Dean, G.J. and Luuring, B.B. 1970. Distribution of aphids in cereal crops. *Annals of Applied Biology* **66:** 485–496.

Dewar, A.M. and Carter, N. 1984. Decision trees to assess the risk of cereal aphid (Hemiptera: Aphididae) outbreaks in summer in England. *Bulletin of Entomological Research* **74:** 387–398.

Dewar, A.M., Woiwood, I. and de Janvry, E.C. 1980. Aerial migrations of the rose-grain aphid, *Metopolophium dirhodum* (Wlk.), over Europe in 1979. *Plant Pathology* **29:** 101–109.

Dietrick, E.J. 1961. An improved back pack motor fan for suction sampling of insect populations. *Journal of Economic Entomology* **54:** 394–395.

Dixon, A.F.G. 1987. Cereal aphids as an applied problem. *Agricultural Zoology Reviews* **2:** 1–57.

Doodson, J.K. and Saunders, P.J.W. 1970a. Some effects of barley yellow dwarf virus on spring and winter cereals in glasshouse trials. *Annals of Applied Biology* **65:** 317–325.

Doodson, J.K. and Saunders, P.J.W. 1970b. Some effects of barley yellow dwarf virus on spring and winter cereals in field trials. *Annals of Applied Biology* **66:** 361–374.

Edwards, M.C., Fetch, T.G. Jr., Schwarz, P.B. and Steffenson, B.J. 2001. Effect of barley yellow dwarf virus infection on yield and malting quality of barley. *Plant Disease* **85**(2)**:** 202–207.

Entwistle, J.C. and Dixon, A.F.G. 1989. The effect of augmenting grain aphid (*Sitobion avenae*) numbers in a field of winter wheat in spring on the aphid's abundance in summer and its relevance to forecasting outbreaks. *Annals of Applied Biology* **114:** 397–408.

Gill, C.C. 1969. Annual variation in strains of barley yellow dwarf virus in Manitoba and the occurrence of greenbug-specific isolates. *Canadian Journal of Botany* **47:** 1277–1283

Gill, C.C. and Chong, J. 1979. Cytopathological evidence for the division of barley yellow dwarf virus isolates into two subgroups. *Virology* **95:** 59–69.

Halbert, S. and Voegtlin, D. 1995. Biology and taxonomy of vectors of barley yellow dwarf viruses. In: 'Barley Yellow Dwarf – 40 Years of Progress' (ed. C.J. D'Arcy and P.A. Burnett), APS Press, St. Paul, Minnesota, pages 217–258.

Jenkyn, J.F. and Plumb, R.T. 1983. Effects of fungicides and insecticides applied to spring barley sown on different dates in 1976–1979. *Annals of Applied Biology* **102**(3)**:** 421–433.

Jones, M.G. 1979. Abundance of aphids on cereals from before 1973 to 1977. *Journal of Applied Ecology* **16:** 1–22.

Kennedy, T.F. and Connery, J. 2001. Barley yellow dwarf virus in winter barley in Ireland: yield loss and timing of autumn aphicides in controlling the MAV-strain. *Irish Journal of Agricultural and Food Research* **40:** 55–70.

Kolbe, W. 1969. Studies on the occurrence of different aphid species as the cause of cereal yield and quality losses. *Pflanzenschutz-Nachrichten Bayer* **22:** 171–204.

Lee, G., Wratten, S.D. and Kenyi, K.B.L. 1981. The effects of growth stage in cereals on yield reductions caused by aphids. *Proceedings of the British Crop Protection Conference – Pests and Diseases* **2:** 449–456.

Lister, R.M. and Ranieri, R. 1995. Distribution and economic importance of barley yellow dwarf. In: 'Barley Yellow Dwarf – 40 Years of Progress' (ed. C.J. D'Arcy and P.A. Burnett), APS Press, St. Paul, Minnesota, pages 29–53.

Mann, J.A., Harrington, R., Carter, N. and Plumb, R.T. 1997. Control of aphids and barley yellow dwarf virus in spring-sown cereals. *Crop Protection* **16**(1)**:** 81–87.

Mann, B.P., Wratten, S.D., Poehling, M. and Borgemeister, C. 1991. The economics of reduced-rate insecticide applications to control aphids in winter wheat. *Annals of Applied Biology* **119:** 451–464.

Martin, R.R. and D'Arcy, C.J. 1995. Taxonomy of barley yellow dwarf viruses. In: 'Barley Yellow Dwarf – 40 Years of Progress' (ed. C.J. D'Arcy and P.A. Burnett), APS Press, St. Paul, Minnesota, pages 203–214.

McKirdy, S.J. and Jones, R.A.C. 1996. Use of imidacloprid and newer generation synthetic pyrethroids to control the spread of barley yellow dwarf luteovirus in cereals. *Plant Disease* **80**(8)**:** 895–901.

Pierre, J.S. and Dedryver, C.A. 1984. Un modele de regression multiple applique ala prevision des pullulations d'un puceron des cereales, *Sitobion avenae* F., sur ble d'hiver. *Acta Oecologica, Oecologia Applicata* **5**(2)**:** 153–172.

Pierre, J.S. and Dedryver, C.A. 1985. Un modele de prevision des pullulations du puceron *Sitobion avenae* sur ble d'hiver. *Phytoma* **369:** 13–17.

Plantegenest, M., Pierre, J.S., Caillaud, C.M., Simon, J.C., DeDryver, C.A. and Cluzeau, S. 1996. A model to describe the reproductive rate in the aphid *Sitobion avenae* (Hemiptera: Aphididae): A case study. *European Journal of Entomology* **93:** 545–553.

Plumb, R.T. 1974. Properties and isolates of barley yellow dwarf virus. *Annals of Applied Biology* **77:** 87–91.

Plumb, R.T. 1983. Barley yellow dwarf virus – a global problem. In: 'Plant Virus Epidemiology' (ed. R.T. Plumb and J.M Thresh), Blackwell Scientific Publications, Oxford, pages 185–198.

Plumb, R.T. 1995. Epidemiology of barley yellow dwarf in Europe. In: 'Barley Yellow Dwarf – 40 Years of Progress' (ed. C.J. D'Arcy and P.A. Burnett), APS Press, The American Phytopathological Society, St. Paul, Minnesota, pages 107–127.

Prior, R.N.B. 1975. Key for the field identification of apterous and alate cereal aphids with photographic illustrations. Ministry of Agriculture, Fisheries and Food (Publications), Middlesex HA5 2DT, UK, 21 pages.

Rochow, W.F. 1969. Biological properties of four isolates of barley yellow dwarf virus. *Phytopathology* **59:** 1580–1589.

Rochow, W.F. 1970. Barley yellow dwarf virus. In: 'Descriptions of Plant Viruses', No. 32, Commonwealth Mycological Institute and Association of Applied Biologists, Kew, Surrey, England.

Rochow, W.F. 1979. Comparative diagnosis of barley yellow dwarf by serological and aphid transmission tests. *Plant Disease* **63:** 426–430.

Rochow, W.F. 1982. Identification of barley yellow dwarf viruses: Comparison of biological and serological methods. *Plant Disease* **66:** 381–384.

Ryden, K. 1990. Chemical control of barley yellow dwarf in spring oats. In: 'World Perspectives on Barley Yellow Dwarf' (ed. P.A. Burnett). *Proceedings of the International Workshop* (6–11 July 1987), Udine, Italy, CIMMYT, Mexico, pages 468–470.

Sommerfeld, M.L., Gildow, F.E. and Frank, J.A. 1993. Effects of single or double infections with *Helminthosporium avenae* and barley yellow dwarf virus on yield components of oats. *Plant Disease* **77:** 741–744.

Stroyan, H.L.G. 1952. The identification of aphids of economic importance. *Plant Pathology* **1:** 9–14; 42–48; 92–99; 123–129.

Sunderland, K.D., Crook, N.E., Stacey, D.L. and Fuller, B.T. 1987. A study of feeding by polyphagous predators on cereal aphids using ELISA and gut dissection. *Journal of Applied Ecology* **24:** 907–933.

Tatchell, G.M., Plumb, R.T. and Carter, N. 1988. Migration of alate morphs of the bird cherry aphid (*Rhopalosiphum padi*) and implications for the epidemiology of barley yellow dwarf virus. *Annals of Applied Biology* **112:** 1–11.

Taylor, L.R., Palmer, J.M.P., Dupuch, M.J., Cole, J. and Taylor, M.S. 1981. A handbook for the rapid identification of alate aphids of Great Britain and Europe. In: 'Euraphid – Rothamsted 1980', Part 11, (ed. L.R. Taylor), Rothamsted Experimental Station, Harpenden, England, pages 1–171.

Tottman, D.R., Makepeace, R.J. and Broad, H. 1979. An explanation of the decimal code for the growth stages of cereals, with illustrations. *Annals of Applied Biology* **93:** 221–234.

Vincent, J.R., Lister, R.M. and Larkins, B.A. 1991. Nucleotide sequence analysis and genomic organization of the NY-RPV isolate of barley yellow dwarf virus. *Journal of General Virology* **72:** 2347–2355.

Watt, A.D. 1979. The effect of cereal growth stages on the reproductive activity of *Sitobion avenae* and *Metopolophium dirhodum*. *Annals of Applied Biology* **91:** 147–157.

Wiktelius, S. 1988. Why is the bird cherry-oat aphid a pest in Sweden? In: 'Ecological Implications of Contemporary Agriculture'. Ecological Bulletins, No. 39, 114–115.

Wiktelius, S. and Ekbom, B.S. 1985. Aphids in spring sown cereals in central Sweden. Abundance and distribution 1980–1983. *Zeitschrift fur Angewandte Entomologie* **100:** 8–16.

Wratten, S.D. 1975. The nature of the effects of the aphids *Sitobion avenae* and *Metopolophium dirhodum* on the growth of wheat. *Annals of Applied Biology* **79:** 27–34.

Wratten, S.D. 1978. Effects of feeding position of the aphids *Sitobion avenae* and *Metopolophium dirhodum* on wheat yield and quality. *Annals of Applied Biology* **90:** 11–20.

Wratten, S.D. and Redhead, P.C. 1976. Effects of aphids on the growth of wheat. *Proceedings of the Association of Applied Biologists, Annals of Applied Biology* **84:** 437–440.

Received 22 April 2004