HGCA

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DEVELOPMENT AND VALIDATION OF DECISION SUPPORT METHODOLOGY FOR CONTROL OF BARLEY YELLOW DWARF VIRUS

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DEVELOPMENT AND VALIDATION OF DECISION SUPPORT METHODOLOGY FOR CONTROL OF BARLEY YELLOW DWARF VIRUS

by

R HARRINGTON[1], J A MANN[1], A J BURGESS[1], S J TONES[2], R ROGERS[2], G N FOSTER[3], S BLAKE[3], S F MORRISON[3], L WARD[4], I BARKER[5], D MORGAN[5] AND K F A WALTERS[5]

[1] IACR-Rothamsted, Harpenden, Hertfordshire AL5 2JQ
[2] ADAS, Mamhead Castle, Mamhead, Exeter, Devon EX6 8HD
[3] SAC, Auchincruive, Ayr KA6 5HW
[4] Queen's University, Newforge Lane, Belfast BT9 5PX
[5] CSL, Sand Hutton, York YO4 1LZ

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CONTENTS

SUMMARY

Objective

The objective of the project was to develop an effective, user-friendly, field specific system for assessing the need to control the aphid vectors of BYDV. An existing regional scale trapping system is used to assess how many winged aphids carrying the virus enter crops in autumn (primary infection). A mathematical model was developed under MAFF funding to capture the effect of weather on the development, reproduction, movement and survival of aphids and this is used to determine how much secondary spread of the virus there has been from the initial foci. The model was tested against independent data collected at three sites. To assess how the regional risk translates to a field-specific risk a major survey was done to examine the characteristics of fields, which make them prone to BYDV problems. The whole system is designed to fit within the DESSAC decision support system.

Epidemiology of BYDV in the UK

BYDV is transmitted only by aphids. The main vectors in the UK are the bird cherry - oat aphid (*Rhopalosiphum padi*) and the grain aphid (*Sitobion avenae*). PAV is the most common isolate but MAV and RPV are also present. Virus enters crops as a result of winged aphids flying in from reservoir hosts, which comprise many grass species. Direct transfer from previous crops or volunteers may also occur but this is not considered here. Spread of the virus is a result of offspring of the colonisers moving through the crop when conditions permit.

Measuring primary infection

Suction traps are used to record numbers of aerial bird cherry - oat aphids in autumn. Numbers alighting per unit area of crop are estimated from the significant relationship found between numbers in suction traps and numbers on sticky wire traps placed directly over crops. The proportion of these that comprises the colonising female form and the proportion carrying virus is estimated from past averages. Numbers of aphids per plant are calculated on the basis of planting density. The number of foci of infection is adjusted according to the expected number of within-crop flights made by alighting individuals on the basis of laboratory trials. A constant low rate of colonisation of grain aphid is assumed as numbers are below levels for reliable quantification using suction traps.

Modelling virus spread

The model unit is a single plant. Virus isolates are not distinguished. The model is temperature driven and aphids grow, reproduce, move and die on the basis of algorithms developed from experimentation within this project and from the literature. The effects of temperature on virus acquisition and inoculation efficiencies and latent periods are also accounted for. Rain and wind are not yet included as driving variables. Output is currently in the form of percentage plants infected. Yield and economic data are not yet incorporated. A sensitivity analysis identified the number of infectious winged aphid immigrants, dispersal rate of wingless aphids, low temperature aphid mortality and virus latent period in the plant as the most critical factors.

Model validation

The model output for aphid and virus incidence was tested against independent data collected from small plots at three contrasting sites over two years for two of the sites and one year for the other. Subplots were sprayed at different times during the autumn and winter to halt further spread of BYDV, and BYDV incidence was assessed in spring. Aphid populations were simulated well in three of the five trials, but were lower than predicted in the other two. Final virus incidence was predicted well in the same three trials but its progress curve was not always predicted accurately.

Field characteristics

Over three growing seasons, 623 unsprayed cereal crops were surveyed in autumn for aphid abundance and in spring for BYDV incidence. Values for forty five categories of field characteristic were recorded and a multivariate analysis used to assess their relationships with aphids and BYDV. Aphid and virus incidences were strongly correlated. There was more BYDV ($P<0.01$) in earlier sown crops, crops closer to the sea, crops around which arable land was less dominant, and in east (MAV) and south west (PAV) facing crops.

Development of a decision support system (DSS)

The model will run under the DESSAC decision support system and there has been close liaison with the DESSAC team. The model needs to be greatly simplified in order to run fast enough within the DSS. Further quantification of aphid winter mortality is needed. There remain difficulties in monitoring colonising *S. avenae*. The next stage is to test the model on a commercial scale.

INTRODUCTION

Barley yellow dwarf virus is often described as the 'yellow plague' of cereals. It is transmitted only by aphids, and its spread can only be controlled by avoiding or removing those aphids. The problem is that by the time the plants are yellow the damage has been done. The virus might therefore be better described as the 'invisible plague' as symptoms cannot be seen at the time that decisions on control need to be taken. A simple solution is to treat the crop with pyrethroids to ensure that the aphids have no chance of damaging the crop. Such an approach can be justified in the absence of suitable resistant cultivars or a reliable risk assessment, especially in early-sown winter varieties in fields known to be at high risk. However, in most fields, control is not usually necessary. There is evidence for detrimental side effects of pesticides and public pressure to curb their use. This project thus seeks to secure a sound basis for a reliable advisory package so that insecticide usage can be optimised. It is only concerned with autumn-sown wheat and barley crops and assumes that there is no 'green bridge' infection with BYDV as a result of aphids walking onto newly emerged crops from weeds or stubble regrowth. In spring crops, control is rarely necessary and, when there is a risk, control is extremely difficult as infection is due to large numbers of winged aphids invading the crop over a long period of time, and not to secondary spread from a few point sources. The best defence against the 'green bridge' is hygiene or control on the green bridge rather than the crop.

In this report we refer to all known UK virus strains as strains of barley yellow dwarf virus (BYDV), although recent molecular work has indicated that the RPV strain of BYDV should more properly be regarded as a separate virus. The name `cereal yellow dwarf virus' (CYDV) has been proposed. For clarity we have used the older terminology which remains in common usage.

OBJECTIVES

The purpose of this project was to bring together our own and other published results to develop an effective system for assessing the need to control the aphid vectors of BYDV. The aim is to provide a scheme which is field-specific whilst avoiding the need for regular field sampling. To achieve this an existing regional scale trapping system is used to assess how many winged aphids carrying the virus are entering crops in autumn (primary infection). A mathematical model was developed to capture the effect of weather on the development, reproduction, movement and survival of aphids and this is used to determine how much secondary spread of the virus there has been from the initial foci. The model was tested against independent data collected at three sites. To assess how the regional risk translates to a field-specific risk a major survey was done to examine the characteristics of fields, which make them prone to BYDV problems. The whole system is designed to fit within the DESSAC decision support system, which will be the means of interacting with those who need to make decisions.

The mathematical model was developed under funding from the Ministry of Agriculture, Fisheries and Food (Project Code CE0410).

ASSESSING REGIONAL PRIMARY BYDV INFECTION

Introduction

Two aphid species are largely responsible for the spread of BYDV in autumn-sown crops. The grain aphid (*Sitobion avenae*), spends the whole year on grasses of various kinds. The bird cherry - oat aphid (*Rhopalosiphum padi*), may also live on grasses in winter, although many produce eggs on bird cherry trees and hence play little part in the BYDV problem. Thus, in autumn, there is a need to know how many grain aphids and how many of the cereal colonising forms of the bird cherry - oat aphid are entering crops. The network of suction traps (Woiwod & Harrington, 1994) operated by Rothamsted and the Scottish Agricultural Science Agency at East Craigs is vital in this. It is also necessary to know what proportion of these aphids are carrying BYDV and, ideally, which isolate of the virus, as efficiency of transmission is affected by the virus-vector combination.

Methods

Fifteen suction traps (Fig. 1) are emptied every day and the aphids identified and counted. The cereal and bird cherry colonising forms of the bird cherry - oat aphid look identical, but a simple test, developed with the help of HGCA funding, has given the potential to distinguish reliably between the two and hence eliminate the egg-laying form from the calculations (Lowles, 1995). It is also necessary to know the proportion of aphids carrying virus and this can be done from suction trapped aphids using the ELISA (Enzyme-linked immunosorbent assay) technique (Lister & Rochow, 1979). However, these tests require fresh specimens or a special collecting medium (Tatchell *et al.* 1988) and data are currently restricted to Rothamsted (Herts).

To check that the suction traps give a reasonable indication of numbers of aphids colonising fields, samples from sticky wire traps (Labonne *et al.*, 1989) placed horizontally over the crop were compared with samples from the nearby Rothamsted suction trap. The aphids cannot detect the sticky wires and are readily caught. On 9th September 1996, seven traps, each measuring

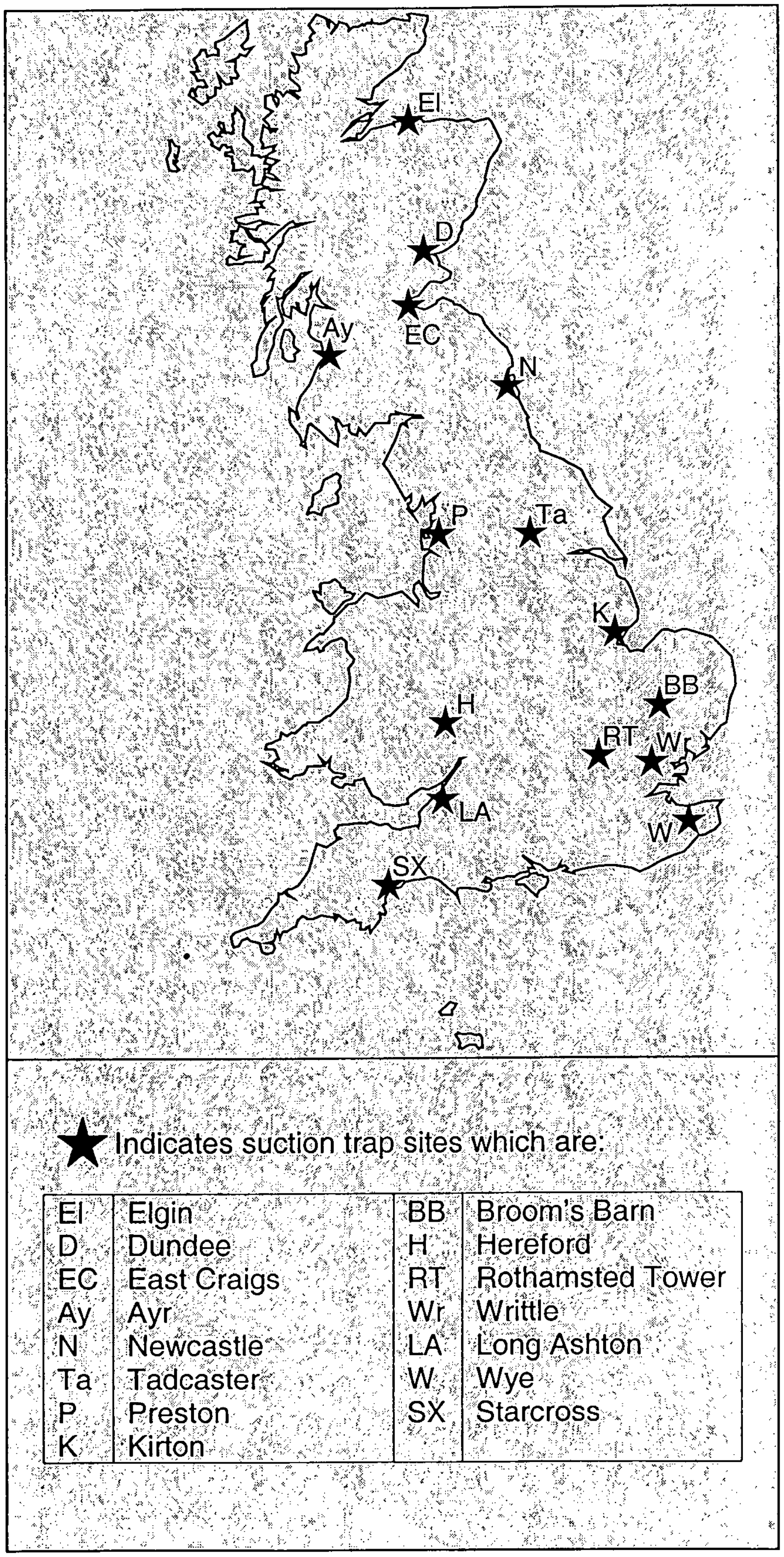


Figure 1. Location of Rothamsted Insect Survey 12.2m suction traps

30cm x 30cm were placed in a 33m x 12m plot of winter barley (cv Puffin) sown on 22nd August 1996 in Osier field, Rothamsted. The traps were replaced at approximately weekly intervals until 3rd November 1996. Cereal aphids were identified and counted. The two forms of bird cherry - oat aphid could not be distinguished when using this type of trap and males and females were not separated.

The experiment was repeated at three sites in the autumn of 1998. One site ('Garden Plots', Rothamsted) was approximately 250m from the suction trap. A second ('New Zealand', Rothamsted) was approximately 750m from the suction trap and the third (Cockayne Hatley) was approximately 39km from the suction trap. This allowed assessment of the affect of distance from the trap on the trap's suitability as an indicator of field invasion by aphids, and also showed the possible extent of variation between two nearby fields. Six traps were placed in each field, on 23rd September (Rothamsted) and 30th September (Cockayne Hatley). They were emptied weekly until 10th November. Male and female aphids were distinguished.

Results

There is a highly significant ($P<0.0001$) linear relationship between logged values of the numbers (male plus female) of bird cherry - oat aphids per sticky wire trap and logged total number in the suction trap over the same period (Fig. 2). There was no significant difference in the relationship between years (Fig. 2) or between the sticky wire trap sites (Table 1).

Table 1. Numbers of bird cherry-oat aphids trapped at three sites in 1998 on sticky wire traps

Site	Garden Plots		New Zealand		Cockayne Hatley	
Date	Female	Male	Female	Male	Female	Male
23/9-29/9	4	0	4	0	No trapping	
30/9-6/10	2	0	7	1	5	0
7/10-13/10	3	0	3	2	3	1
14/10-20/10	1	1	4	0	1	1
21/10-27/10	0	1	1	0	1	0
28/10-3/11	0	1	0	0	0	0
4/11-10/11	0	1	0	0	0	0

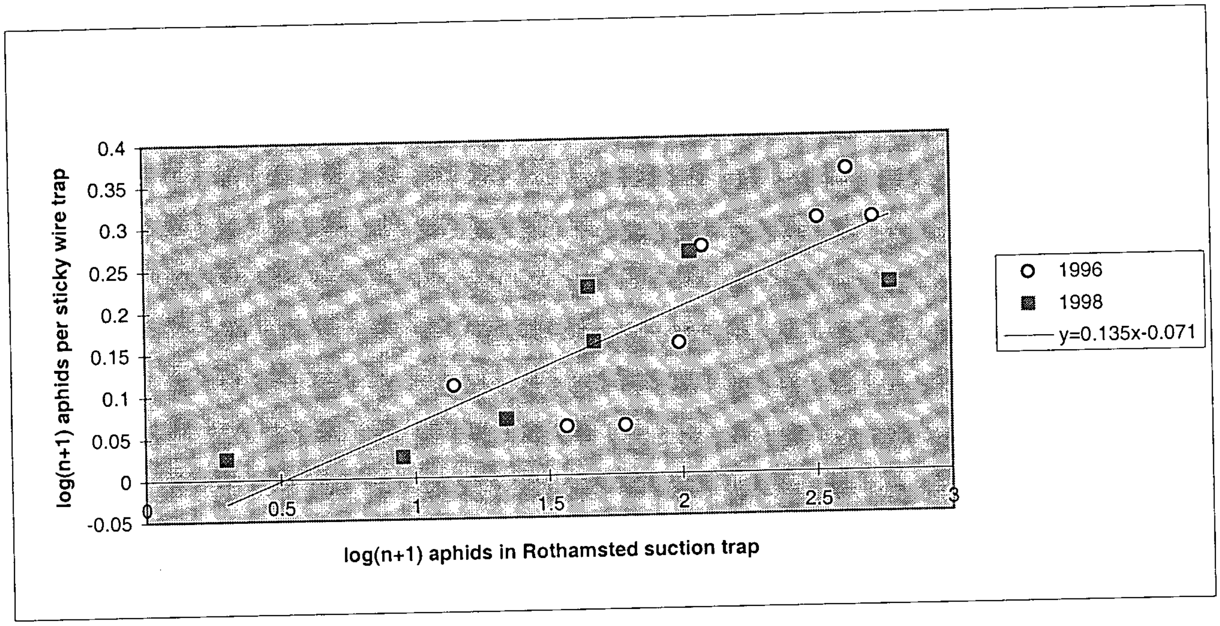


Figure 2. Relationship between total numbers of bird cherry – oat aphids in Rothamsted suction trap and sticky wire traps placed over barley crops.

Discussion and implications for modelling virus spread

The significant relationship between numbers in the sticky wire traps and suction traps allows numbers of cereal-colonising forms of bird cherry - oat aphids in the suction trap to be converted to numbers in the crop using the formula :

$$\log (y+1) = 0.135 \log (x+1) - 0.071 \text{ (Adjusted } r^2 = 0.678, n=15, P<0.0001)$$

where y = number of aphids in a 30cm x 30cm area of crop and x = number in the suction trap.

The lack of a significant difference in numbers of bird cherry - oat aphids in sticky wire traps up to 40km apart suggests that it is reasonable to use this relationship over a wide area. However, it would be useful to have data covering a similar area around other suction trap sites.

In the suction trap during the 1998 experiment, 69% of the bird cherry - oat aphids trapped were female. In the sticky wire traps, 81% of the aphids caught in the same period were female. In a

1.5m suction trap adjacent to the 12.2m trap, 81% of bird cherry - oat aphids trapped were female. The difference is probably due to the tendency of females of cereal colonising forms to fly at a lower level than males and females which colonise bird cherry (Tatchell *et al.*, 1988). It may therefore be preferable to use low level suction traps to estimate the numbers of aphids entering fields, but there is not currently a national network of these.

For the purpose of the model of secondary spread, the aphids are assumed to land at random within a field. Errors as a result of this assumption in estimating the area of crop infected with BYDV are likely to be small.

The grain aphid presents a problem, as it tends to fly in very small numbers in autumn. However, because it is more tolerant of cold than is the bird cherry - oat aphid, it sometimes survives for longer and can be very important in secondary spread of virus. Thus, it must be accounted for in the model. It may be necessary to seed the model with a constant low number of grain aphids in years and regions where none, or very few, are recorded in the suction traps. Alternatively, the model for grain aphid may need to be initiated on the basis of a single field sample once the main migration is over.

MOVEMENT AND FECUNDITY OF WINGED COLONISING APHIDS

Introduction

Spread of the virus due to colonising aphids flying again within a field after arrival in the crop is treated here as part of the primary infection process. Field and laboratory experiments were done to determine how many flights aphids usually make and how many offspring they produce so that the number of foci of infection can be adjusted accordingly.

Methods

Field experiment

Four plots (each 3m x 3m) of winter wheat (cv Mercia) and four plots of winter barley (cv Puffin) were sown on 20th September 1995, and a further four of each on 18th October 1995.

Bird cherry - oat aphids were reared on a natural stand couch grass covered with net cages (0.5m x 0.5m x 1.0m). Three days before the experiment began, all winged aphids were removed from the sides of the cages. Just prior to the experiment, winged aphids for use in the experiment were collected from the sides of the cages and were assumed to have flown within the previous three days.

Ten winged aphids were placed on separate plants inside a mesh cage (0.25m x 0.25m x 0.5m) on each plot on 6th November 1996. All cages were examined each day for ten days. Winged aphids found on the sides of the cages each day were assumed to have flown and were transferred to a new cage, which was also examined on subsequent days, aphids being transferred to another new cage if found on the side. After ten days all plants within each cage were carefully searched for both winged aphids and their offspring.

The experiment was repeated beginning on 21st November.

Laboratory experiment

A laboratory experiment was set up to make more detailed observations of flight and walking by winged aphids under controlled conditions, using a similar experimental design to that in the field. Grain aphids and bird cherry - oat aphids were compared on each of two growth stages (GS 12 and GS 22) of wheat (cv Beaufort) and barley (cv Puffin), with four replicates of each (32 plots total).

Aphids were reared at 18°C, in a daily cycle of 16 hours light and 8 hours dark at a high density to ensure maximum production of winged forms.

Pregerminated seeds were planted in seed trays (54cm x 54cm) in two rows at approximate field density (plants within a row separated by 2cm, rows separated by 12.5cm), each row comprising 10 plants. Plants to be used at GS 12 were grown for one week at 18-20°C and those to be used at GS 22 were grown for three weeks under the same conditions. Just prior to the experiment, mesh cages (0.25m x 0.25m x 0.5m) were placed over the plants and slightly buried in the soil. The wooden frames around the bottom of the cages were coated with fluon[R] to prevent aphids walking up the cage sides.

Four days before the start of the experiment, fourth instar winged aphids were removed from the rearing cultures and placed on virus-infected plants (grain aphids on plants infected with the MAV strain of BYDV and bird cherry - oat aphids on plants infected with the PAV strain). One day later all winged aphids were removed from the sides of the cages. On the first day of the experiment, winged aphids, which had flown to the sides of the cages, were removed for use in the experiment. Winged aphids were marked using green, orange, yellow or white fluorescent powders by placing them in a glass jar with a small amount of powder. One aphid marked with each coloured powder and two unmarked aphids were placed on a separate plant in each cage. All cages were carefully searched three hours later on the first day, and three times on each subsequent day at approximately 0900, 1200 and 1500, for ten days. The sides of the cages were carefully searched for any aphids which had flown, and the position of released winged aphids, and their offspring, on plants within the cage was noted.

Results

Field experiment

Almost all flights occurred within the first four days after release (Fig. 3). The mean number of flights per plot was greater on late sowings than on early sowings and was greater on barley than on wheat, but there was much variability in the data. There were no consistent differences between crop types and sowing dates with respect to numbers of offspring produced, but again there was much variability.

Laboratory experiment

The majority of flights of the bird cherry - oat aphid and all flights of the grain aphid occurred within the first four days after release (Fig. 4). There was a greater number of flights from late-sown plants (GS 12) by both aphid species compared to early-sown plants (GS 22). The number of flights by bird cherry - oat aphids from both wheat and barley was similar, whereas grain aphids flew more from barley plants than from wheat. Bird cherry - oat aphids flew more than grain aphids (Table 2). The majority of winged aphids made no flights, with 27.1% of bird cherry - oat aphids and 14.6% of grain aphids flying at least once. No grain aphids flew more than once. However, 11.5% of bird cherry - oat aphids flew twice and 1% three times (Table 2). Aphid fecundity was not significantly reduced when aphids flew (Fig. 5) compared to aphids that did not fly.

Table 2. Number of flights made by bird cherry - oat and grain aphids and the potential increase in foci of infection.

Aphid	**Number of flights**				**Total**	**Potential**
	0	**1**	**2**	**3**	**aphids**	**foci**
Bird cherry - oat	70	14	11	1	96	135
Grain	82	14	0	0	96	110

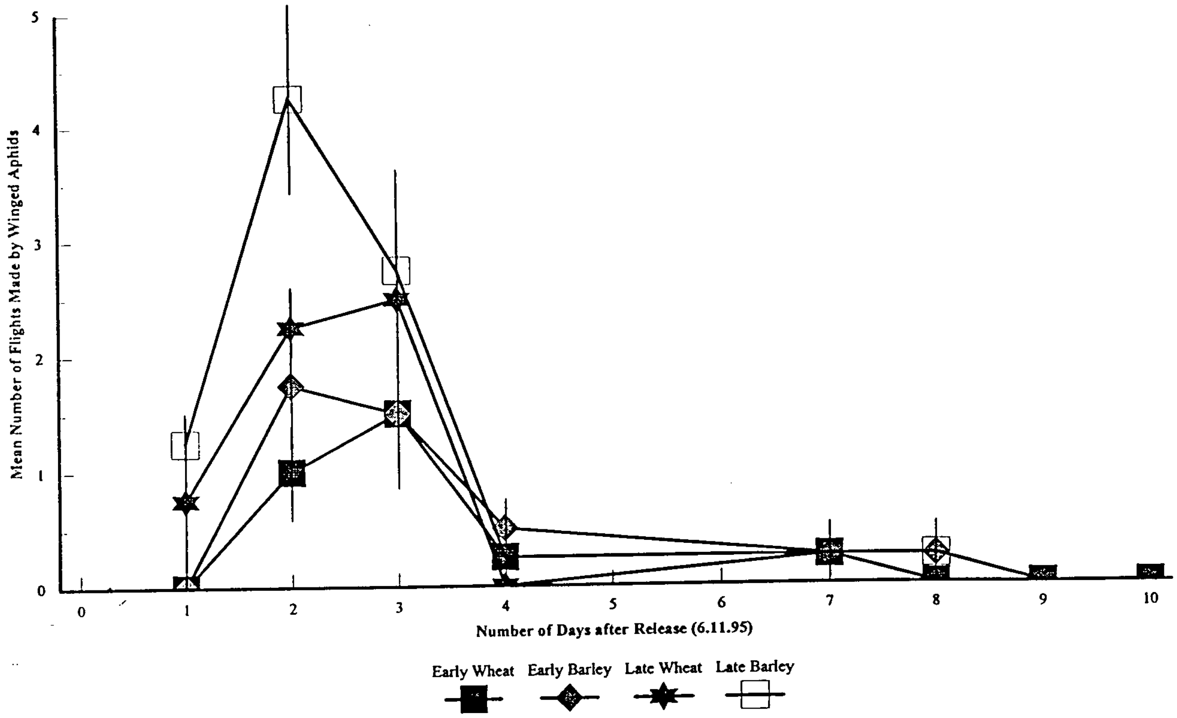


Figure 3a. Mean number of flights per plot (10 winged aphids per plot) over ten days after release on 6 November 1995 when early crops were at GS 21 and late crops at GS 10. Bars are standard errors of the means.

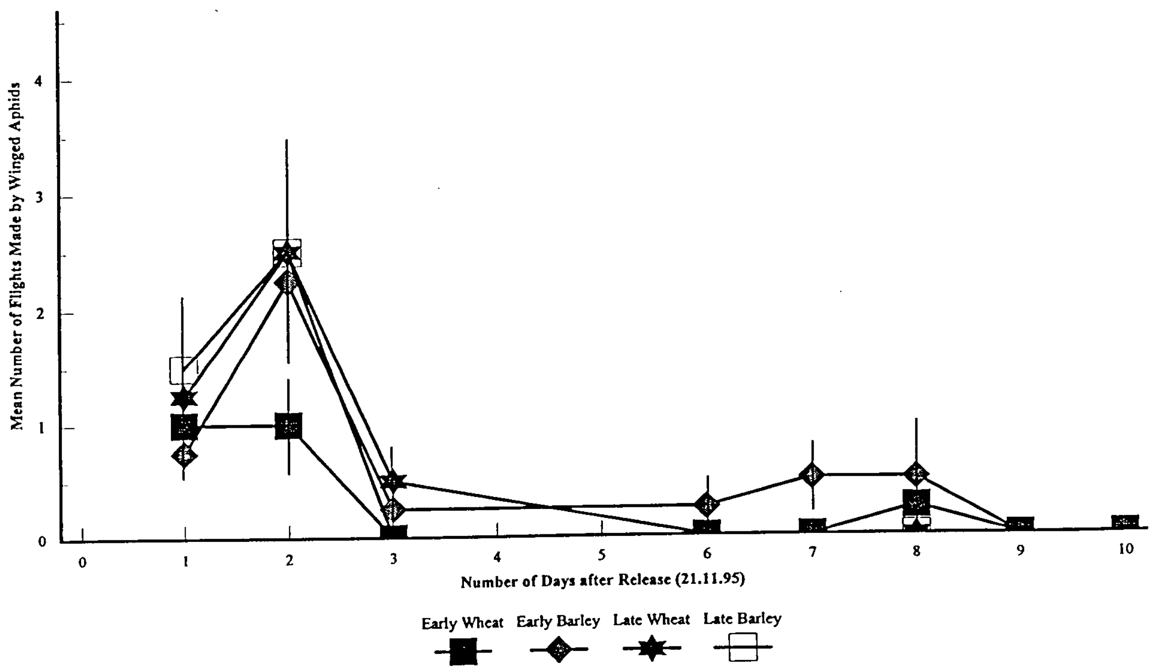


Figure 3b. Mean number of flights per plot (10 winged aphids per plot) over ten days after release on 21 November 1995 when early crops were at GS 22/23 and late crops at GS 12. Bars are standard errors of the means.

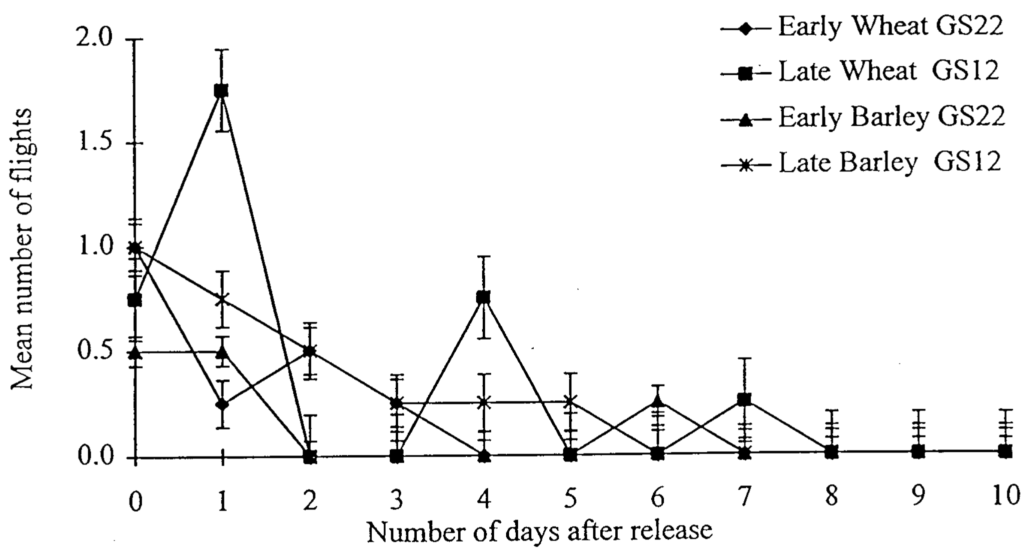


Figure 4a. Mean number of flights per treatment (4 replicates) by bird cherry – oat aphid (6 winged aphids per cage) over ten days from release. Vertical lines denote 2 standard errors.

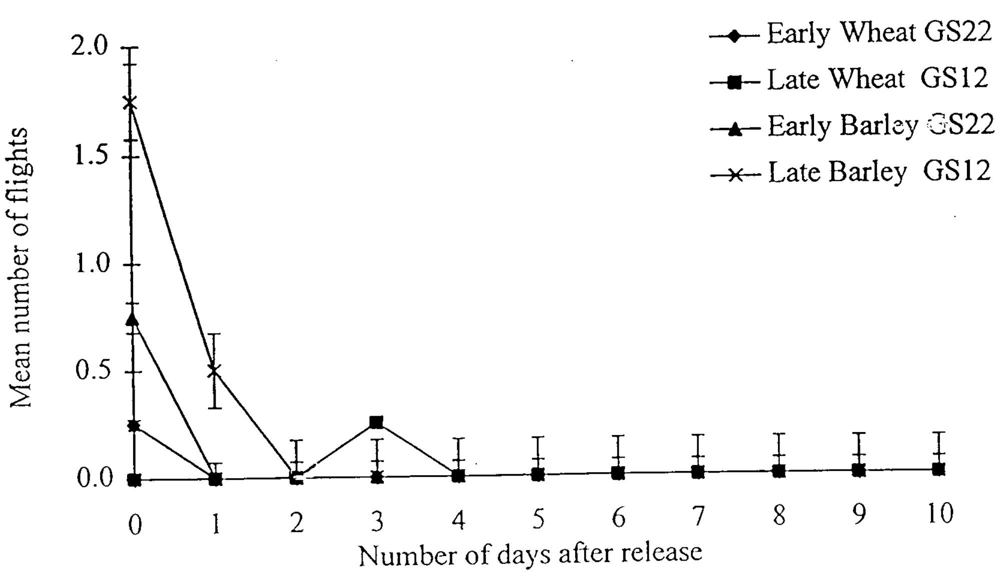


Figure 4b. Mean number of flights per treatment (4 replicates) by grain aphid (6 winged aphids per cage) over ten days from release. Vertical lines denote 2 standard errors.

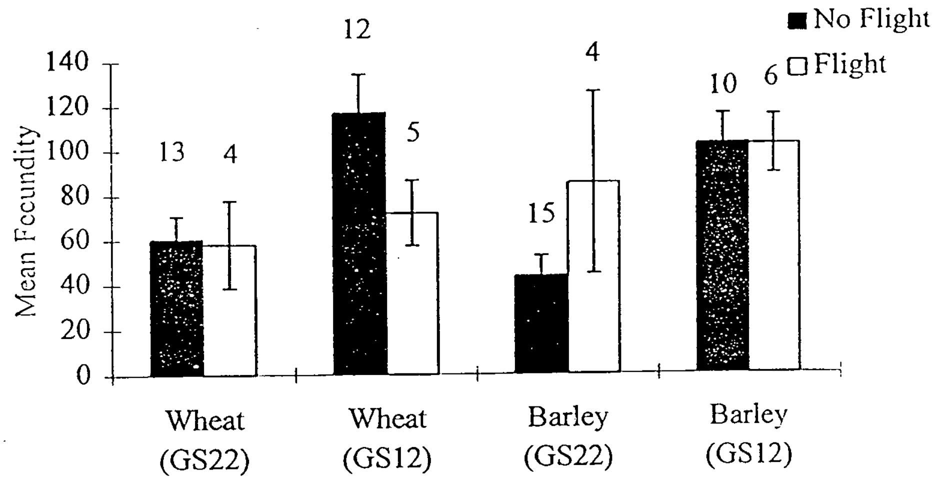


Figure 5a. Comparison of mean fecundity of winged bird cherry – oat aphids that did not fly and those that flew from different growth stages of wheat and barley. Numbers of aphids are shown above each bar. Vertical lines denote 2 standard errors.

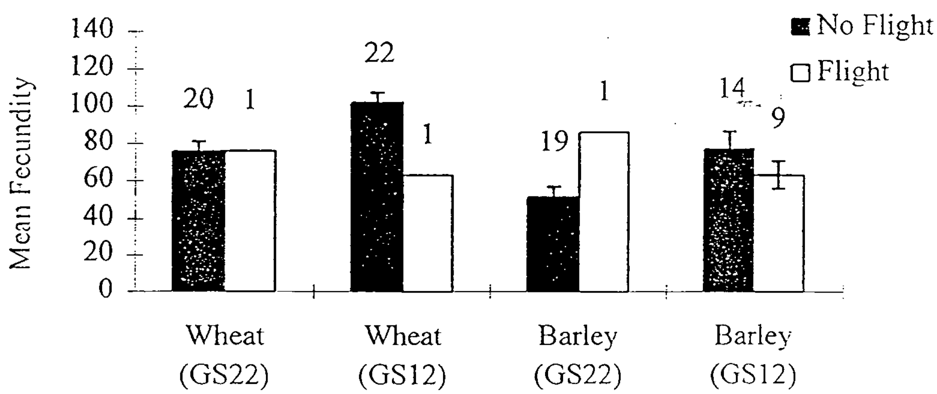


Figure 5b. Comparison of mean fecundity of winged grain aphids that did not fly and those that flew from different growth stages of wheat and barley. Numbers of aphids are shown above each bar. Vertical lines denote 2 standard errors.

Discussion and implications for modelling virus spread

Field experiments support laboratory experiments showing that winged colonising aphids fly within a crop and that flights generally occur only within the first four days after arrival in the crop. Based on the laboratory results, every 100 bird cherry - oat aphids arriving in the crop will lead to 141 foci of infection, and every 100 grain aphids will lead to 115 foci of infection. Differences between crop type and age are not sufficiently clear to warrant account in the model.

FIELD CHARACTERISTICS IN RELATION TO BYDV INCIDENCE

Introduction

The objective of this work was to assess the relationship between field-specific factors and risk of BYDV incidence so that the model of regional risk could be applied to individual fields.

Methods

Over the three growing seasons 1995/6 to 1997/8, farmers left sections of 623 autumn-sown cereal crops untreated with insecticide in order to facilitate this survey. The crops were largely wheat and barley, with a few oats, and were spread throughout the United Kingdom (Fig. 6). Each crop section was surveyed twice, once at the beginning of the winter to assess aphid abundance, and again in the early spring to assess the incidence of BYDV. Many field variables were assessed during these visits (Table 3).

In each field section, 10 or 20 lengths of crop were examined (100m total) and aphids recorded on a scale of 1 - 4: 1 = absent; 2 = < 5 colonies; 3 = 6-50 colonies; 4 = > 50 colonies. An Aphid Index (AI) for each field was calculated by summing the scores for the 10 or 20 lengths sampled as an alternative to the more traditional approach of estimating the absolute total number of aphids per field or per row. This index is sufficient to identify trends and major differences between fields. Temperature, wind, cloud and rain were recorded at the time of sampling aphids.

Virus incidence was assessed visually at the second visit and by ELISA analysis (Lister & Rochow, 1979) from samples taken at the same time. Where possible the strain was identified as MAV, PAV or RPV.

Results

Aphid incidence

Aphids were recorded from 271 fields, 43% of the total. The highest mean Aphid Index (AI) per field was in fields sampled in October. The lowest indices were recorded in December, and no aphids at all were recorded in five fields sampled in January. There was a highly significant negative correlation between aphid numbers and sampling date (Table 4). The number of fields found to support aphids of any species declined from October to December, as did the mean AI. Bird cherry - oat aphid was generally more numerous than grain aphid.

Fewer aphids were found and a lower percentage of the fields contained aphids in 1996/7 than in either 1995/6 or 1997/8. In 1995 (Table 5), the AI remained high during November and although grain aphid declined steeply in December, bird cherry - oat aphid remained relatively abundant, being found in 40% of fields. Only grain aphid numbers were significantly correlated with sampling date in 1995/6. In both 1996/7 (Table 6) and 1997/8 (Table 7) there was a steady decline in both AI and the percentage of infested fields from October to December, for both species. Bird cherry - oat aphid was found in only 8% of fields in December of both years, and grain aphid in 4% of fields in December 1996 and none in December 1997. For this reason, fields sampled in December of 1996 and 1997 were excluded from further analysis of aphid numbers, as were the five fields sampled in January 1998, leaving a total sample size of 514 fields.

The number of aphids found was not correlated with windiness but there was an association with cloud and rain for all species, and with temperature for bird cherry - oat aphid (Table 8). Significantly fewer aphids were found in bright conditions, and more bird cherry - oat aphids were found in warm conditions. It seems likely that the description 'bright' was used most frequently to refer to clear frosty conditions so that the association is with temperature rather than rain, which apparently had little effect either on the presence of aphids or on the efficiency of the searching process.

Table 3. Variables measured in the field survey.

Surrounding land use	**Aspect and shelter**
Amenity/sports/airfield	Field size
Arable	Flat or sloping
Arterial road	if sloping, direction of slope
Fresh water (running)	Distance to highest point within 1 km radius
Fresh water (standing	Direction of highest point within 1 km radius
Grazing pasture	**Soil**
Tidal area	Texture
Moorland	Tilth characteristics
Intensive horticulture	Plant trash
Built-up area	**Position**
Farm buildings	Average altitude
Railway (in use)	Latitude and longitude
Railway (disused)	Grid reference
Uncultivated	Distance to sea
Waste ground	**Previous cropping and present husbandry**
Woodland	Crop in last season
Forestry plantation	if crop was grass, desiccation policy
Set-aside	Crop in last but one season
Shelter belt	Current crop and variety
Field boundary type(s)	Date of planting
Hedgerow	Cultivation details
Road/track	Seed treatments
Uncultivated strip >1m	Pesticide applications
Wall	
Roadside verge	
Water course	

Table 4. The relationship between aphid numbers and sampling date in three seasons. AI = Aphid Index (see text). Aphids = aphids of any species including bird cherry - oat and grain aphids. (** = P < 0.01).

		n	Aphids	Bird cherry – oat aphid	Grain aphid
Correlation of AI with sampling date		623	-0.287**	-0.217**	-0.278**
% fields containing aphids	1995/6-7/8	623	44%	33%	29%
	October 1995-7	56	82%	68%	59%
	November 1995-7	410	47%	35%	34%
	December 1995-7	152	17%	18%	7%
	January 1998	5	0	0	0
Mean AI	1995/6-7/8	623	4.83	2.63	1.66
	October 1995-7	56	11.18	6.28	3.71
	November 1995-7	410	5.20	2.68	1.92
	December 1995-7	152	1.65	1.23	0.25
	January 1998	5	0	0	0
Range in AI			0-76	0-49	0-30

Table 5. The relationship between aphid numbers and sampling date in the 1995/6 growing season. AI = Aphid Index (see text). Aphids = aphids of any species including bird cherry – oat and grain aphids. (** = P < 0.01).

1995/6		**n**	**Aphids**	**Bird cherry – oat aphid**	**Grain aphid**
Correlation of AI with sampling date		234	-0.106	-0.049	-0.189**
% of fields containing aphids	Oct-Dec 1995	234	62%	51%	41%
	October 1995	22	63%	50%	32%
	November 1995	164	66%	54%	48%
	December 1995	48	42%	40%	17%
Mean AI	Oct-Dec 1995	234	6.64	3.97	2.00
	October 1995	22	5.77	3.23	2.27
	November 1995	164	7.47	4.33	2.36
	December 1995	48	4.23	3.10	0.62
Range in AI			0-61	0-49	0-20

Table 6. The relationship between aphid numbers and sampling date in the 1996/7 growing season. AI = Aphid Index (see text). Aphids = aphids of any species including bird cherry - oat aphid and grain aphid. (** = P < 0.01).

1996/7		**n**	**Aphids**	**Bird cherry - oat aphid**	**Grain aphid**
Correlation of AI with sampling date		254	-0.230**	-0.174**	-0.223**
% of fields containing aphids	October - December 1996	254	17%	12%	9%
	October 1996	9	67%	44%	67%
	November 1996	160	18%	13%	9%
	December 1996	80	10%	8%	4%
	January 1997	5	0	0	0
Mean AI	October - January 1996/7	254	1.27	0.83	0.38
	October 1996	9	7.00	4.71	2.67
	November 1996	160	1.36	0.87	0.41
	December 1996	80	0.52	0.42	0.10
	January 1997	5	0	0	0
Range in AI			0-27	0-23	0-17

Table 7. The relationship between aphid numbers and sampling date in the 1997/8 growing season. AI = Aphid Index (see text). Aphids = aphids of any species including bird cherry – oat and grain aphids. (*** = P<0.001).

1997/8		**n**	**Aphids**	**Bird cherry - oat aphid**	**Grain aphid**
Correlation of AI with sampling date		135	-0.436***	-0.399***	-0.300***
% of fields containing aphids	Oct-Dec 1997	135	62%	43%	48%
	October 1997	25	100%	82%	80%
	November 1997	86	63%	38%	52%
	December 1997	24	12%	8%	0%
Mean AI	October - December 1997	135	8.33	3.66	3.45
	October 1997	25	17.44	9.76	5.36
	November 1997	86	7.94	2.87	3.85
	December 1997	24	0.25	0.17	0
Range in AI			0-76	0-46	0-30

Table 8. The relationship of Aphid Index (AI) with weather conditions on the day of sampling.

		Mean AI		
Weather conditions	**n**	**Aphids**	**Bird cherry - oat aphid**	**Grain aphid**
Bright	167	1.97	1.05	0.62
Fair	95	6.48	3.94	1.88
Overcast	221	6.47	3.52	2.23
Light rain	79	4.53	2.34	1.73
Heavy rain	47	5.53	2.60	2.34
Cold	384	4.67	2.31	1.77
Mild	119	4.88	2.71	1.80
Warm	82	6.04	4.38	0.93

Virus incidence

Virus incidence was generally low, particularly in the crop of 1996/7. Some damaging outbreaks occurred in the 1997/8 crop. The map of the combined incidence of virus over all three years (Fig. 7) shows that risk is highest in coastal areas with the exceptions of the coast from Suffolk to Tyne and Wear (low incidence) and inland north of London (high incidence). The latter was due to MAV and PAV in 1997/8 (Figs 8 and 9 respectively). RPV distribution is shown in Fig. 10.

Of the 623 fields sampled over the three years, 177 (28%) tested positive BYDV. Virus was most prevalent in 1997/8 with 45% of fields infected (Table 9). The MAV strain was notably more common in that year. The RPV strain was least common in all years.

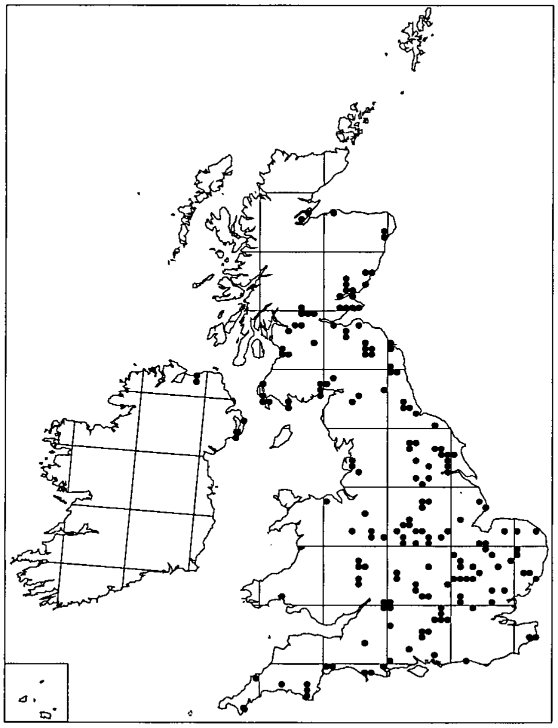


Figure 6a. Distribution of all fields in 1995-1998.

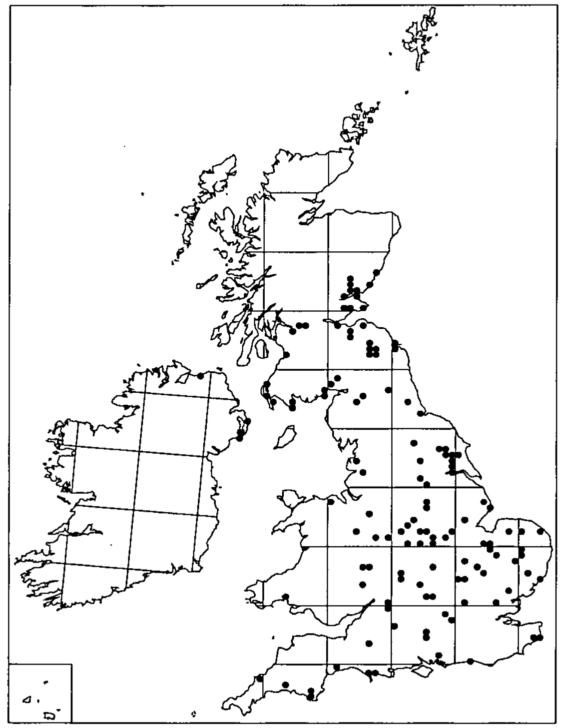


Figure 6b. Distribution of all fields in 1995/6.

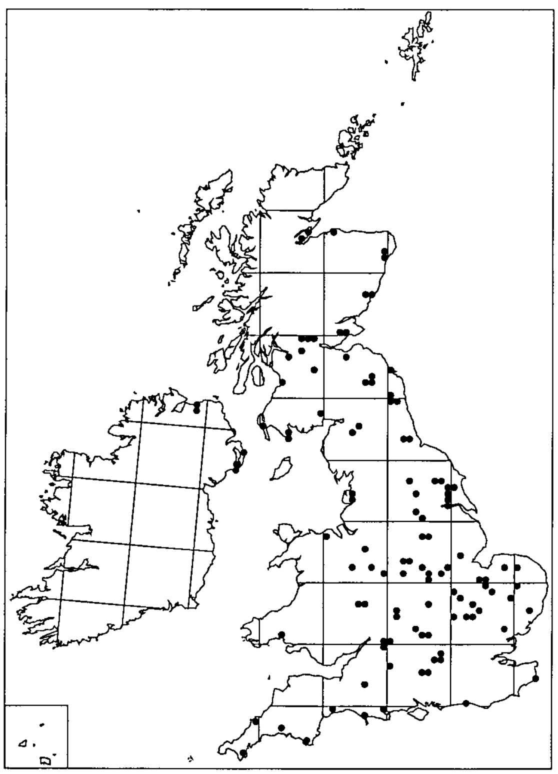


Figure 6c. Distribution of all fields in 1996/7.

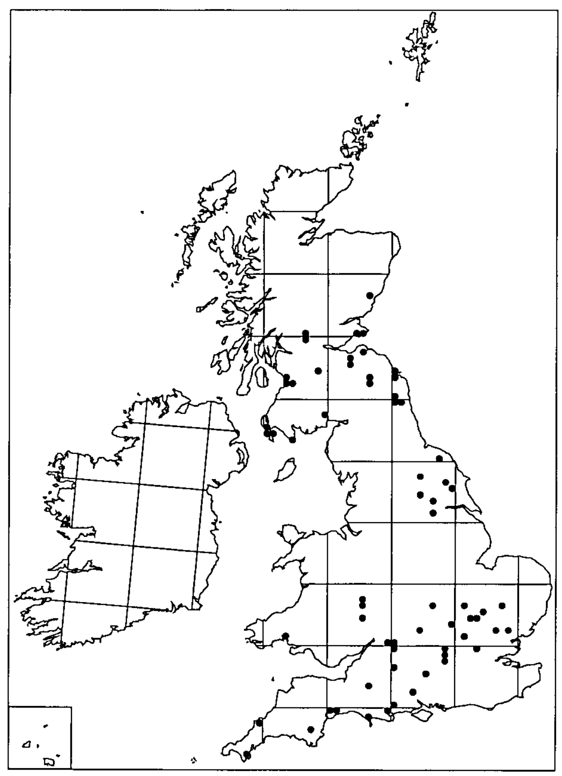


Figure 6d. Distribution of all fields in 1997/8.

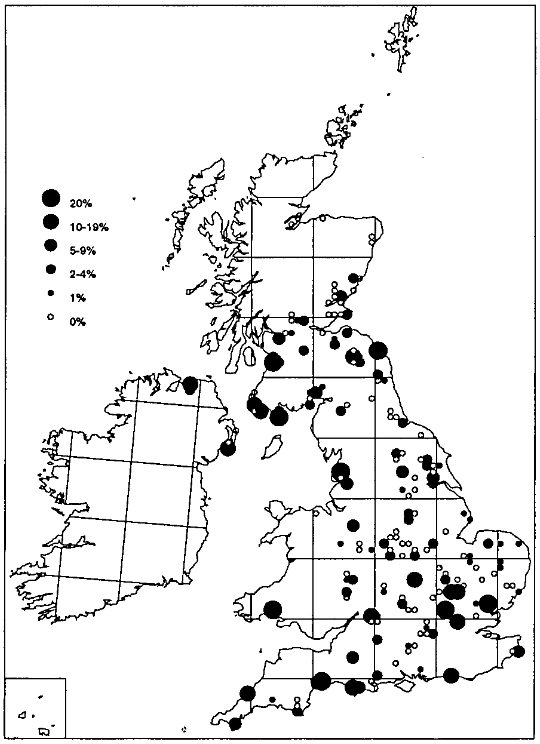


Figure 7a. Distribution of total BYDV in all fields in 1995-1998.

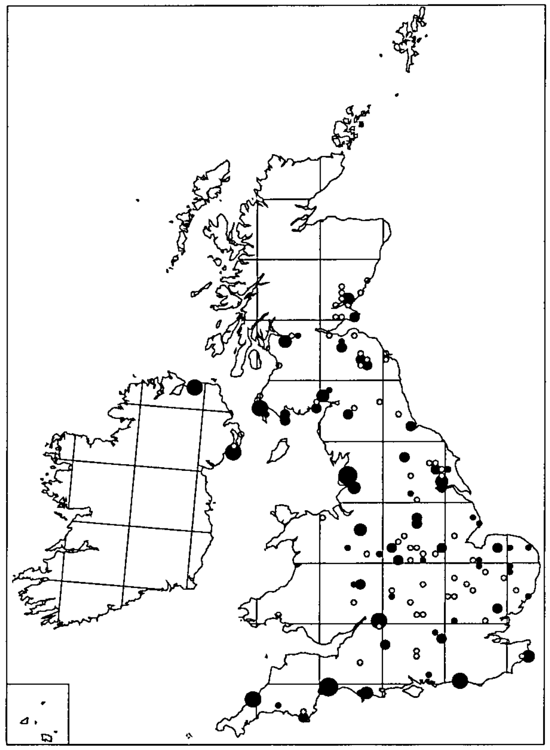


Figure 7b. Distribution of total BYDV in all fields in 1995/6. Symbols coding as in Figure 7a.

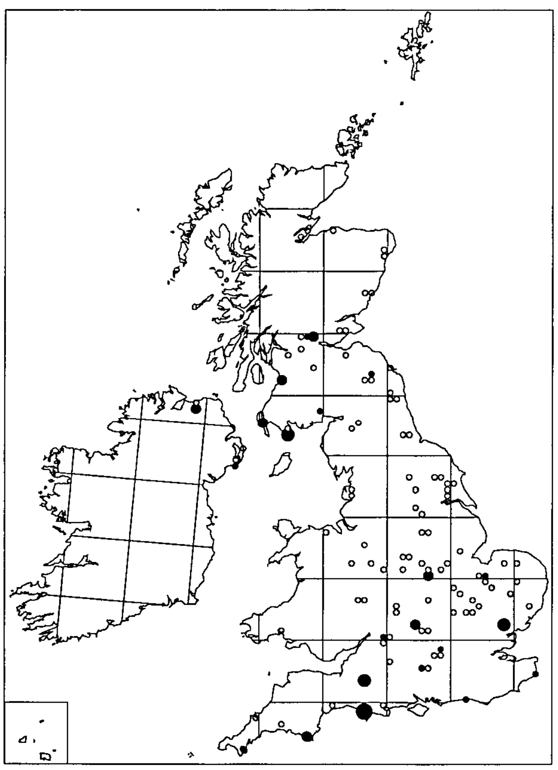


Figure 7c. Distribution of total BYDV in all fields in 1996/7. Symbols coding as in Figure 7a.

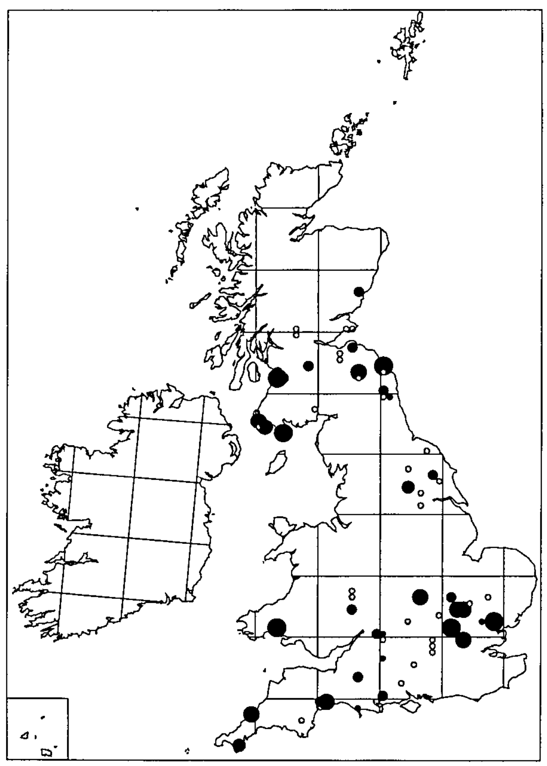


Figure 7d. Distribution of total BYDV in all fields in 1997/8. Symbols coding as in Figure 7a.

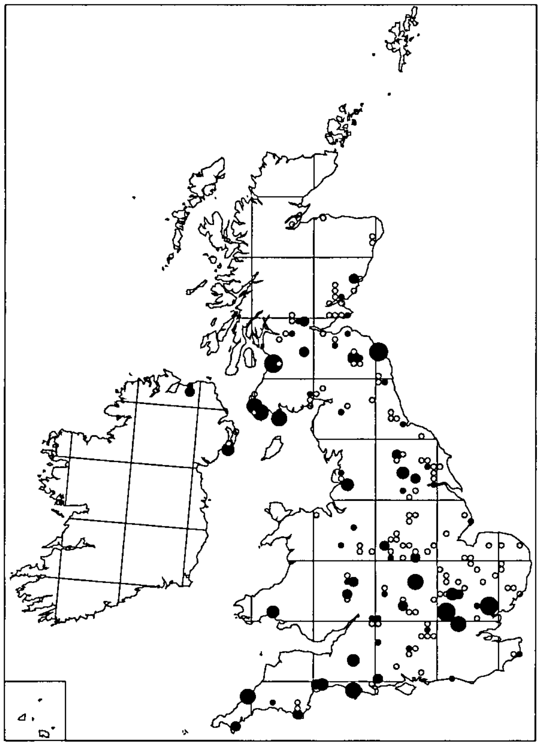


Figure 8a. Distribution of MAV serotype in all fields in 1995-1998. Symbols coding as in Figure 7a.

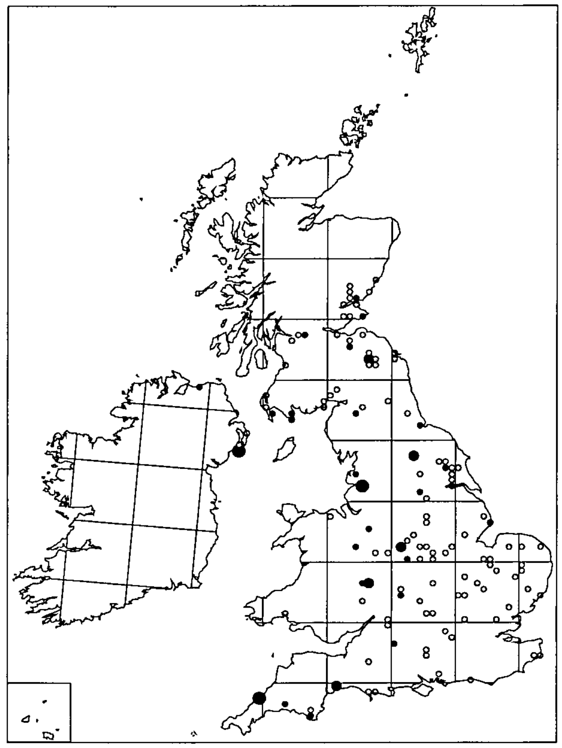


Figure 8b. Distribution of MAV serotype in all fields in 1995/6. Symbols coding as in Figure 7a.

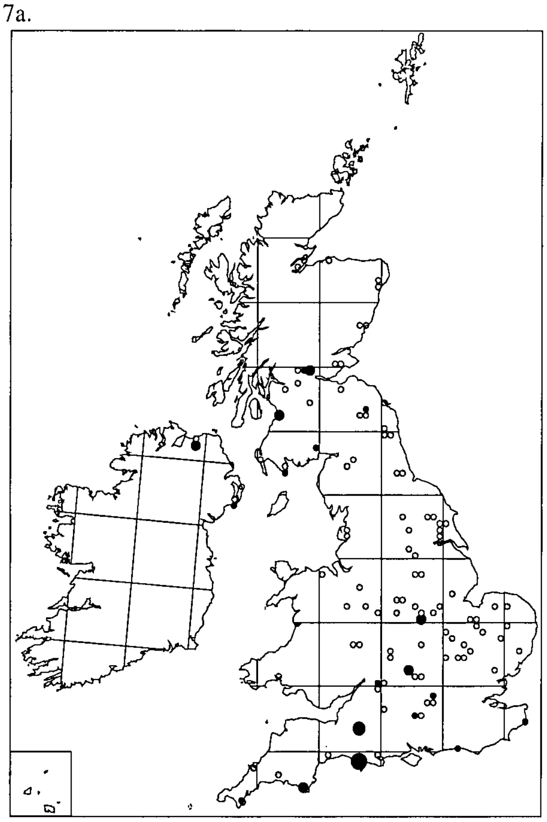


Figure 8c. Distribution of MAV serotype in all fields in 1996/7. Symbols coding as in Figure 7a.

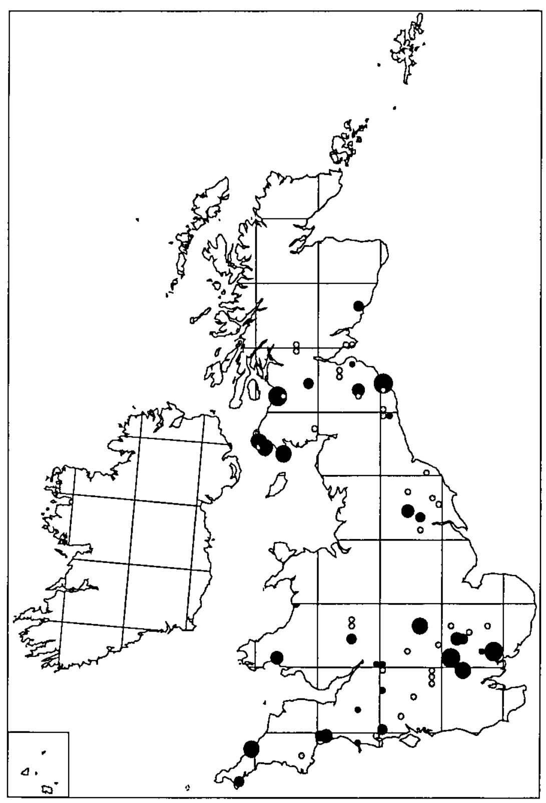


Figure 8d. Distribution of MAV serotype in all fields in 1997/8. Symbols coding as in Figure 7a.

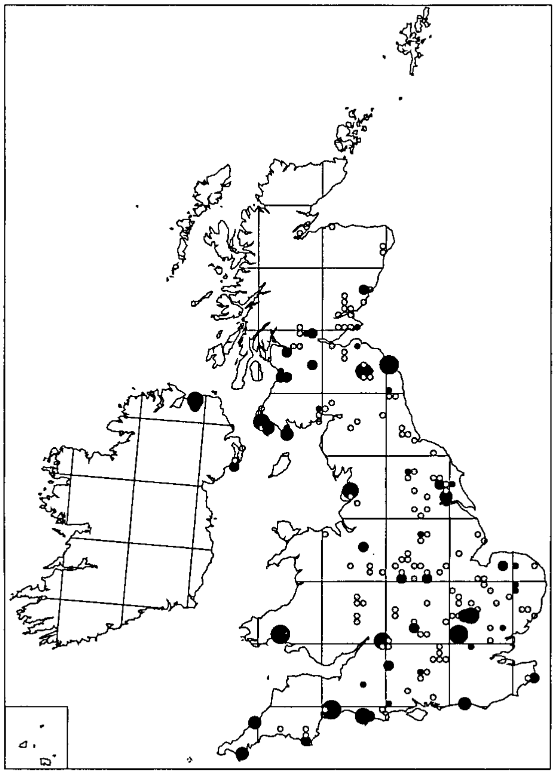


Figure 9a. Distribution of PAV serotype in all fields in 1995-1998. Symbols coding as in Figure 7a.

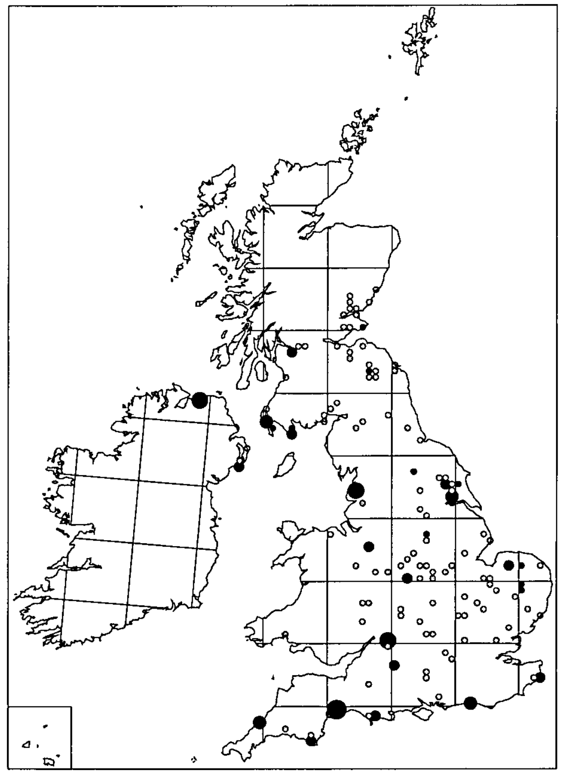


Figure 9b. Distribution of PAV serotype in all fields in 1995/6. Symbols coding as in Figure 7a.

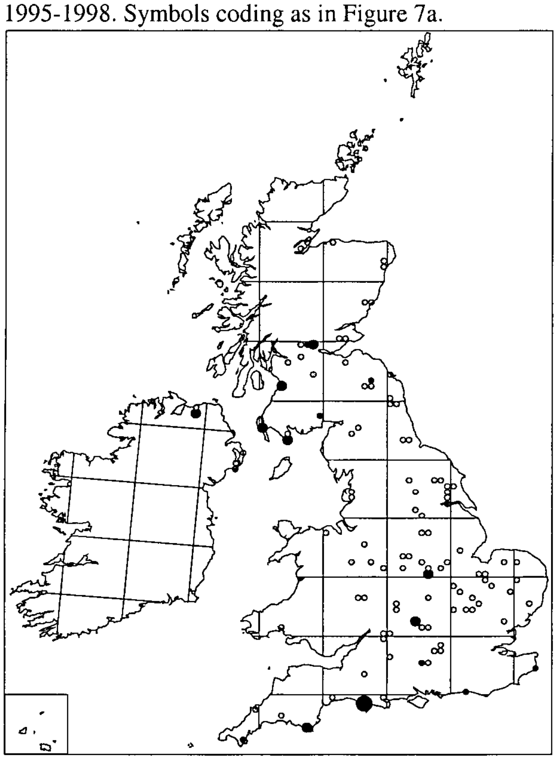


Figure 9c. Distribution of PAV serotype in all fields in 1996/7. Symbols coding as in Figure 7a.

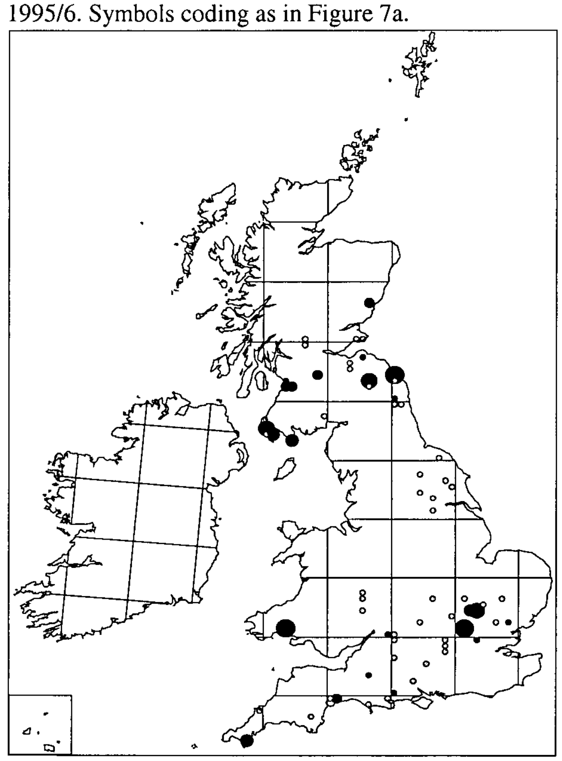


Figure 9d. Distribution of PAV serotype in all fields in 1997/8. Symbols coding as in Figure 7a.

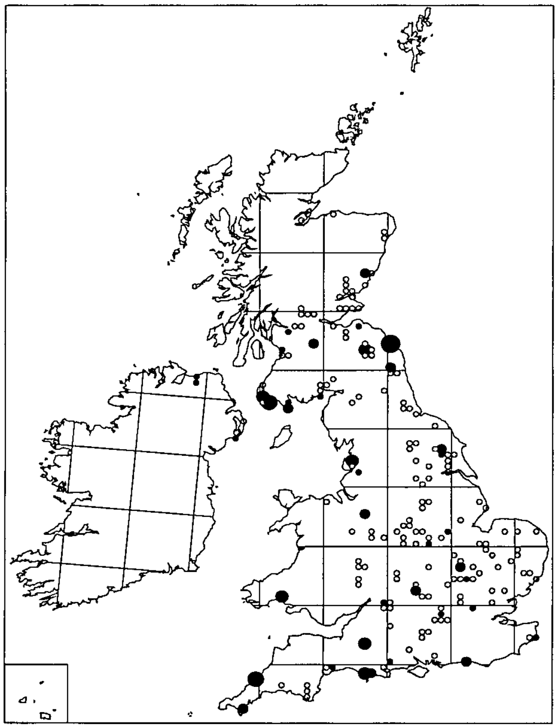


Figure 10a. Distribution of RPV serotype in all fields in 1995-1998. Symbols coding as in Figure 7a.

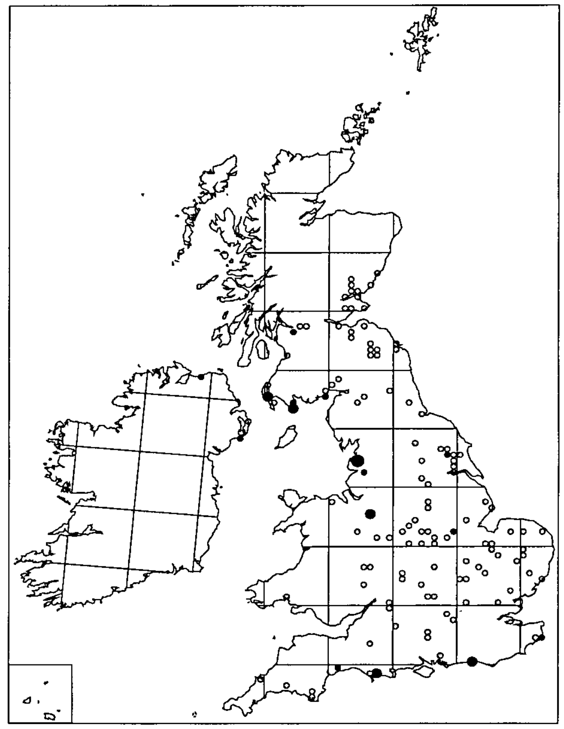


Figure 10b. Distribution of RPV serotype in all fields in 1995/6. Symbols coding as in Figure 7a.

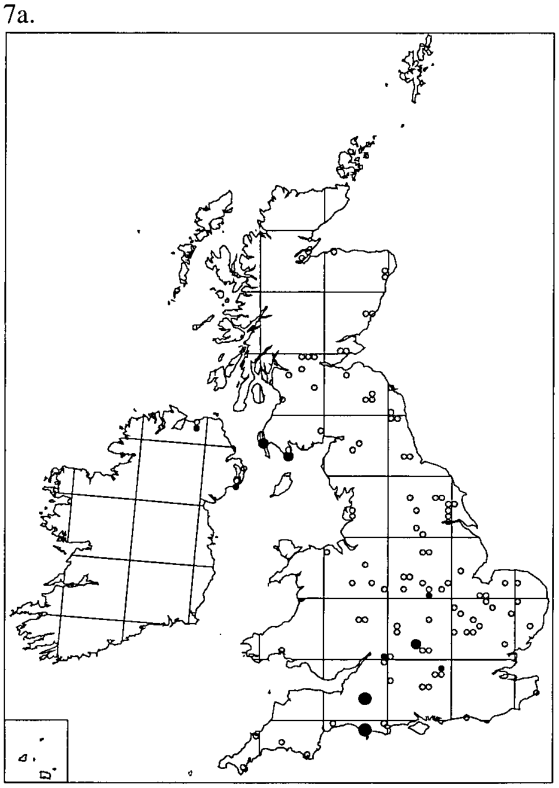


Figure 10c. Distribution of RPV serotype in all fields in 1996/7. Symbols coding as in Figure 7a.

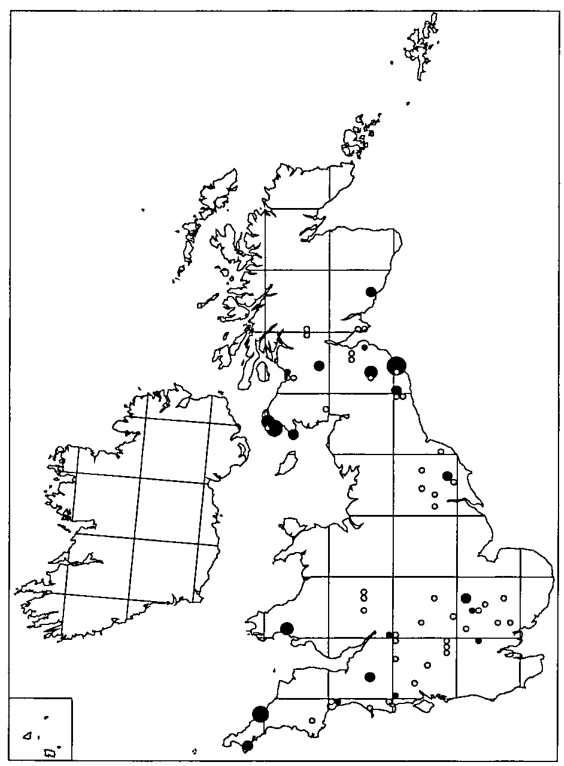


Figure 10d. Distribution of RPV serotype in all fields in 1997/8. Symbols coding as in Figure 7a.

Table 9. The percentage of fields testing positive for three BYDV strains in three years.

Year	n	BYDV +ve	MAV +ve	PAV +ve	RPV +ve
1995/6 – 7/8	623	28%	14%	15%	9%
1995/6	234	38%	15%	16%	8%
1996/7	254	10%	10%	7%	5%
1997/8	135	45%	38%	27%	20%

Co-occurrence of BYDV strains

A total of 711 leaves gave a positive reaction for BYDV. A number of these contained more than one strain (Table 10).

Table 10. The co-occurrence of BYDV strains in individual leaves

No. leaves positive for	Strains present			
MAV	MAV only	MAV + PAV	MAV + RPV	MAV + PAV + RPV
391	299 (77%)	12 (3%)	21 (5%)	59 (15%)
PAV	PAV only	PAV + MAV	PAV + RPV	PAV + MAV + RPV
329	248 (75%)	12 (4%)	10 (3%)	59 (18%)
RPV	RPV only	RPV + MAV	RPV + PAV	RPV + MAV + PAV
152	62 (41%)	21 (14%)	10 (7%)	59 (39%)

For both MAV and PAV, about three-quarters of the leaves testing positive for BYDV contained only one strain, but for RPV this figure was about 40% with an almost equal number containing all three strains. RPV was thus found much more frequently in association with other strains than either of the commoner strains.

Visual assessment of BYDV

A visual assessment of BYDV infection on a scale from 0 to 4 was made in each field at the time of leaf sampling. One hundred of the 623 fields were assessed as showing symptoms of BYDV. The visual assessment of symptoms correlated very well with positive ELISA response for virus (Table 11).

Table 11. The relationship between visual assessment of symptoms and positive ELISA response for BYDV.

Visual assessment	n	mean BYDV by ELISA	P
Absent	523	0.70	< 0.001
Present	100	5.17	(Mann-Whitney test)
0 = 0 % infected	523	0.70	
1 = < 5 % infected	67	3.18	< 0.001
2 = 6 – 25 % infected	23	6.13	(Kruskal-Wallis test)
3 and 4 = 26 –100 % infected	10	16.30	

Relationships between aphid numbers and virus incidence

Of the 514 fields analysed with respect to aphids, 164 (32%) contained BYDV. There was a strong relationship between AI and the occurrence of BYDV (Table 12). The PAV strain was associated most significantly with bird cherry - oat aphid and the MAV strain with grain aphid. The RPV strain was significantly correlated with the total number of aphids, but not with either species on its own.

Table 12. Correlation coefficients for Aphid Index with BYDV strains (* P < 0.05; ** P < 0.01; *** P < 0.001).

	BYDV +ve	MAV +ve	PAV +ve	RPV +ve
Aphids	0.435***	0.370***	0.329***	0.081*
Bird cherry – oat aphid	0.408***	0.267***	0.352***	0.044
Grain aphid	0.334***	0.398***	0.186**	0.063

Influence of field characteristics on aphid and virus incidence

The relationships between virus incidence and field factors are explored here, taking one factor group at a time. Linear Modelling is used in the last section in order to identify the most important factors dictating virus incidence from amongst those measured.

Crop species, sowing date and virus incidence

In general, there was more virus in barley than in wheat (Table 13). This was significant for MAV in 1997/8, this outbreak being largely responsible for the significance of the total MAV level over the three seasons, and for total virus infection in 1997/8. There was more virus in early-sown than late-sown crops (Table 14). These factors are closely related in that the difference in sowing date of barley and wheat was highly significant in all three seasons (P < 0.001), with median sowing dates of late September for barley and early October for wheat.

Table 13. Comparison of mean infection levels of barley and wheat crops by BYDV strains, with results of *t*-tests (log n + 1) and Mann-Whitney U-tests (* =P < 0.05 ** = P < 0.01 *** =P < 0.001)

	Sample size (n)		**Mean no. of leaves infected**		***t***	**U**
	Barley	Wheat	Barley	Wheat		
BYDV						
1995/6	95	136	1.54	1.38	0.78	0.95
1996/7	108	144	0.25	0.33	0.13	0.35
1997/8	73	62	4.58	2.29	*0.03	***0.0005
1995 – 97	276	342	1.84	1.10	0.10	0.48
MAV						
1995/6	95	136	0.37	0.19	0.48	0.89
1996/7	108	144	0.20	0.22	0.34	0.52
1997/8	73	62	3.41	1.29	*0.02	0.06
1995 – 97	276	342	1.11	0.40	**0.01	0.39
PAV						
1995/6	95	136	0.73	0.54	0.93	0.61
1996/7	108	144	0.21	0.17	0.46	0.61
1997/8	73	62	1.67	0.97	0.15	0.33
1995 – 97	276	342	0.78	0.46	0.25	0.97
RPV						
1995/6	95	136	0.07	0.19	0.11	0.43
1996/7	108	144	0.08	0.10	0.65	0.80
1997/8	73	62	1.15	0.55	0.32	0.41
1995 – 97	276	342	0.36	0.22	0.66	0.99

Table 14. The effect of sowing date on the incidence of BYDV in barley and wheat crops in three seasons combined.

Sowing date	n	BYDV infection (mean + s.d.)	MAV infection (mean + s.d.)	PAV infection (mean + s.d.)	RPV infection (mean + s.d.)
Before mid-September	52	2.37 (6.199)	1.02 (3.257)	1.17 (3.445)	0.19 (0.658)
Mid – late September	271	1.97 (5.519)	1.05 (3.541)	0.79 (3.274)	0.42 (2.188)
Early – mid-October	192	0.82 (2.374)	0.28 (1.408)	0.32 (1.120)	0.20 (1.081)
After mid-October	74	0.53 (2.602)	0.07 (0.344)	0.32 (2.228)	0.08 (0.361)
K (d.f. = 3)		11.75	8.49	4.58	1.02
P		<0.01	<0.05	NS	NS

Cultivars

Data on ten or more crops were available for seven wheat and seven barley cultivars (Table 15). The levels of aphid infestation and virus infections varied significantly between cultivars (Kruskal-Wallis tests indicate differences significant at $P<0.01$). The most widely represented wheat cultivar, Riband, had the highest levels of aphid infestation but Reaper had more than twice as much virus as the next wheat. Three of the barleys had virus infection near to the level of Reaper, but only one of these cultivars, Fighter, had high levels of aphid infestation. The correlation between aphid and virus levels was poor (Fig. 11).

There was, however, a highly significant relationship between the levels of infestation of bird cherry - oat aphid and grain aphid when data were grouped by cultivar ($P< 0.001$ for both numbers of aphid colonies per crop and for the square roots of the percentages of crops infested). Assuming that some cultivars are more susceptible than others to aphid attack irrespective of species, this supports the rankings of cultivar in terms of susceptibility to aphids, and lends support in turn to the rankings in terms of susceptibility to virus. Although the two species of aphid have distinct distributions, conditions favouring the detection of one species will similarly affect the chances of finding the other. Some correlation is therefore to be expected, but not at the extreme levels observed (89% of variation accounted for using either percentage infestation or number of colonies observed).

An additional possibility affecting the observed performance of cultivars might be the preference for use in areas particularly prone to virus attack. This would be the case for crops used primarily for stockfeed.

It is not clear to what extent, if at all, BYDV tolerance has been built into winter barleys and wheats in the UK (see Burnett & Plumb, 19XX). The results here demonstrate a need for more classical trialling of cultivars under pressure from both aphids and viruses. The main conclusion is that some cultivars appear to have higher resistance to BYDV than others, and that this is not necessarily correlated with susceptibility to aphids.

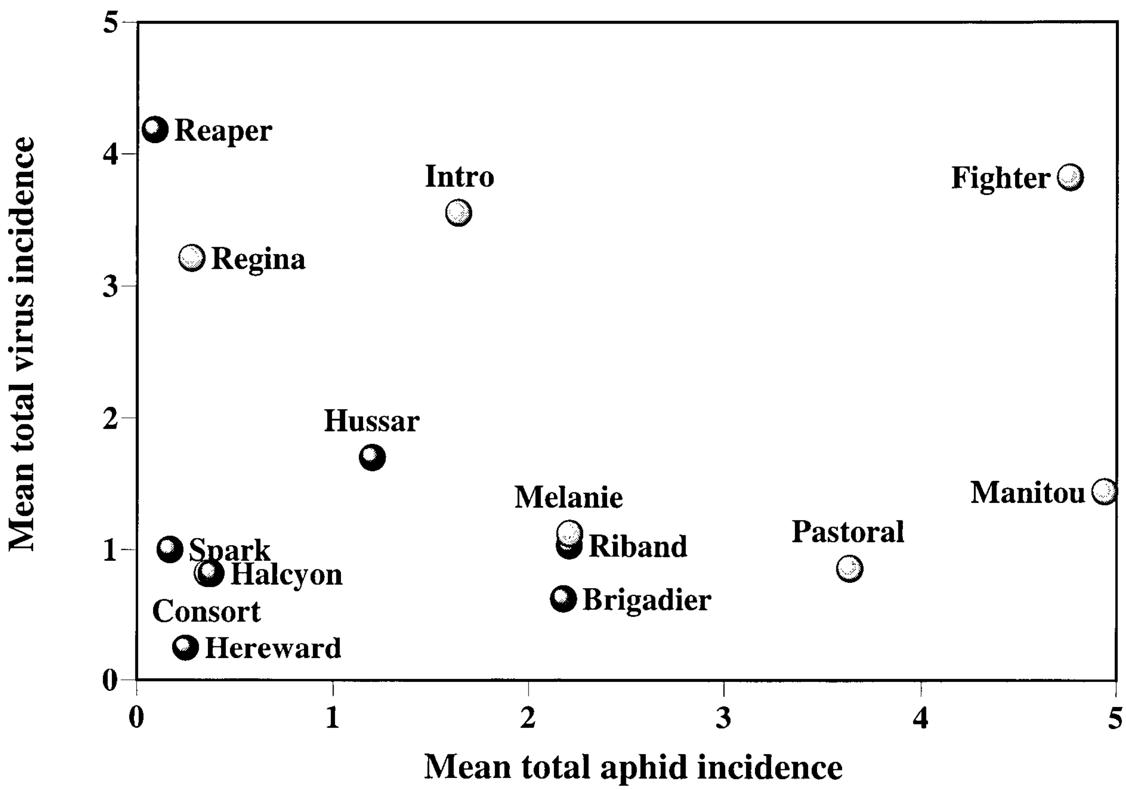


Figure 11. Scatter plot of BYDV incidence in relation to aphid incidence for seven wheat cultivars (dark symbols) and seven barley cultivars (light symbols). Note that cv. Halcyon has same values as wheat cv. Consort.

Table 15. Virus infection levels summarised in respect of cultivars with ten or more observations.

	No. crops	% crops with virus	No. positive samples per crop				Mean no. aphid colonies per crop			% of crops infested	
			All virus	MAV	PAV	RPV	All aphids	Bird cherry - oat aphid	Grain aphid	Bird cherry – oat aphid	Grain aphid
Wheat											
Reaper	11	55	4.18	0.64	3.27	0.82	0.09	0.09	0	1	0
Hussar	10	30	1.70	0.10	0.60	0.30	1.20	0.50	0.70	3	3
Riband	119	25	1.03	0.42	0.27	0.15	2.21	1.22	0.99	44	45
Spark	12	33	1.00	0.08	0.17	0.67	0.17	0.17	0	2	0
Consort	11	27	0.82	0.09	0.27	0.18	0.36	0.27	0.09	3	1
Brigadier	51	25	0.63	0.13	0.29	0.21	2.18	1.18	1.00	15	9
Hereward	12	8	0.25	0	0	0.08	0.25	0.25	0	2	0
Barley											
Fighter	34	35	3.82	2.79	0.91	0.38	4.76	2.76	2.00	16	16
Intro	11	45	3.55	1.09	2.55	0.18	1.64	1.09	0.55	3	3
Regina	14	64	3.21	2.79	0.43	0.07	0.28	0.07	0.21	1	2
Manitou	16	37	1.44	0.56	0.63	0.25	4.94	2.31	2.63	10	11
Melanie	17	12	1.12	0.59	0.94	0.71	2.212	1.24	0.88	4	7
Pastoral	36	28	0.86	0.06	0.42	0.06	3.64	1.78	1.86	19	16
Halcyon	11	45	0.82	0.36	0.64	0.55	0.36	0.18	0.18	2	1

Surrounding land use and field boundary type

Although there was no significant effect overall of the presence of arable land, non-arable usage, in particular grassland, moorland, woodland, uncultivated/waste land was associated with higher aphid numbers (Table 16). Disturbed land, as indicated by buildings and main roads, and running water were also associated with higher aphid numbers. Aphid numbers were generally higher next to setaside, but this was not significant for the main two species individually. The absence of hedgerows was associated with more aphids, which should be contrasted with the effect of walls.

There were fewer significant differences between virus levels than between aphid densities (Table 17). Land use types associated with higher mean levels of BYDV were wasteland, running water and sheltered areas. Reduced levels were associated with the dominance of arable land and the presence of arterial roads and railways in use.

Aphid levels were higher in association with grass or weedy land and this was to a limited degree the case for virus incidence. This generality lends credence to the results but the higher aphid numbers associated with arterial roads cannot be reconciled to the lower levels of virus. Perhaps the most important finding was the lack of impact of setaside land on the incidence of BYDV.

Apparent effects of any individual land use type may be complicated by the co-occurrence of types (Table 18). For example, of the 74 fields close to railways, 80 % were also close to arterial roads.

Table 16. Mean Index of all aphid species (AI), bird cherry – oat aphid and grain aphid for nineteen land-use categories and six field boundary types. For each row, values with the same superscript are significantly different at the 5 % significance level (Mann-Whitney U test). Emboldened figures are the values found to be significantly higher than their opposing values.

	n	**mean AI**	**mean bird cherry – oat aphid**	**mean grain aphid**	**n**	**mean AI**	**mean bird cherry – oat aphid**	**mean grain aphid**
Land use type			Present				Dominant	
Arable	103	5.95	2.82	2.21	403	5.66	3.15	1.92
			Present				Absent	
Grazing	148	2.16^{a}	1.28^{b}	0.72^{c}	366	**7.22**^{a}	**3.85**^{b}	**2.51**^{c}
Moorland	486	5.17^{a}	2.88^{b}	1.67^{c}	28	**16.04**^{a}	**7.07**^{b}	**7.32**^{c}
Woodland	136	2.90^{a}	1.69^{b}	0.94^{c}	378	**6.79**^{a}	**3.62**^{b}	**2.37**^{c}
Plantation	456	5.83	3.15	2.06	58	5.17	2.83	1.45
Uncultivated	276	4.19^{a}	2.46^{b}	1.27^{c}	238	**7.58**^{a}	**3.87**^{b}	**2.83**^{c}
Wasteland	366	5.24^{a}	2.78^{b}	1.81	148	**7.05**^{a}	**3.94**^{b}	2.46
Tidal	474	5.47^{a}	2.97^{b}	1.87	40	**9.25**^{a}	**4.75**^{b}	3.50
Setaside	359	5.23^{a}	2.78	1.91	155	**6.99**^{a}	3.88	2.19
Amenity	456	5.58	3.06	1.87	58	7.21	3.50	2.95
Arterial road	150	4.09^{a}	2.54	1.12^{c}	364	**6.45**^{a}	3.35	**2.35**^{c}
Running water	204	2.97^{a}	2.02^{b}	0.75^{c}	310	**7.60**^{a}	**3.83**^{b}	**2.82**^{c}
Standing water	389	5.44	3.05	1.79^{c}	125	6.75	3.32	2.62^{c}
Horticulture	497	5.79	3.15	1.98	17	4.82	2.12	2.47
Built-up area	380	5.18^{a}	2.74^{b}	1.80	134	**7.40**^{a}	**4.16**^{b}	2.53
Farm buildings	78	3.67^{a}	2.04^{b}	1.33^{c}	436	**6.14**^{a}	**3.30**^{b}	**2.11**^{c}
Railway in use	451	5.72	3.11	1.96	63	6.05	3.16	2.22
Disused railway	458	5.54	3.06	1.88	56	7.54	3.54	2.93
Shelter belt	433	5.80	3.09	2.02	81	5.57	3.25	1.83
Field boundary								
Hedgerow	76	**6.99**^{a}	**4.49**^{b}	1.95	438	5.55^{a}	2.87^{b}	2.00
Road/track	233	6.17	2.95	2.44	281	5.42	3.24	1.63
Uncultivated strip	292	4.38^{a}	2.31^{b}	1.48^{c}	222	**7.58**^{a}	**4.17**^{b}	**2.67**^{c}
Wall	435	4.78^{a}	2.56^{b}	1.63^{c}	79	**11.15**^{a}	**6.14**^{b}	**4.00**^{c}
Roadside verge	429	5.98	3.13	**2.16**^{c}	85	4.64	3.04	1.15^{c}
Watercourse	382	5.49	2.98	1.88^{c}	132	6.54	3.50	**2.33**^{c}

Table 17. Mean infection levels of BYDV for presence and absence of nineteen types of surrounding land use and six types of field boundary, with results of tests for significant differences. Emboldened figures are the levels found to be significantly higher than the opposing values.

	n	mean BYDV	n	mean BYDV	F	tests
Land use type		Present		Dominant		
Arable	106	**2.76**	500	1.13	2.07	NS (U) P < 0.05 (t)
		Absent		Present		
Grazing	174	1.04	440	1.60	1.44	NS (U, t)
Moorland	583	1.37	31	2.68	1.76	NS (U, t)
Woodland	154	1.20	460	1.52	1.24	NS (U, z)
Plantation	537	1.54	77	0.75	1.69	NS (U, t)
Uncultivated	323	1.28	291	1.61	1.23	NS (U, z)
Wasteland	440	1.20	174	**2.04**	1.55	NS (U) P < 0.05 (t)
Tidal	569	1.29	45	3.33	2.14	NS (U, t)
Setaside	411	1.51	203	1.30	1.15	NS (U, z)
Amenity	549	1.32	65	2.48	1.70	NS (U, t)
Arterial road	165	**1.98**	449	1.24	1.35	P < 0.05 (U, t)
Running water	245	0.80	369	**1.89**	2.04	NS (U) P < 0.01 (t)
Standing water	459	1.41	155	1.52	1.08	NS (U, z)
Horticulture	594	1.42	20	1.85	1.48	NS (U, t)
Built-up area	462	1.22	152	2.09	1.48	NS (U, t)
Farm buildings	98	1.50	516	1.44	1.03	NS (U, z)
Railway in use	540	**1.49**	74	1.08	1.32	P < 0.01 (U) P < 0.05 (z)
Disused railway	543	1.42	71	1.59	1.10	NS (U, z)
Shelter belt	521	1.40	93	**1.68**	1.20	P < 0.05 (U) NS (z)
Field boundary						
Hedgerow	108	1.27	506	1.48	1.18	NS (U, z)
Road/track	264	1.44	350	1.44	1.03	NS (U, z)
Uncultivated strip	343	1.24	21	1.69	1.31	NS (U, z)
Wall	519	1.40	95	1.65	1.27	NS (U, z)
Roadside verge	522	1.42	92	1.54	1.05	NS (U, z)
Watercourse	456	1.29	158	1.87	1.44	NS (U, z)

Table 18. The proportions of each of 19 land use types found in association with every other land use type.

	Land use type	n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	Arable	606		0.7	0.1	0.8	0.1	0.5	0.3	0.1	0.3	0.1	0.7	0.6	0.3	0.0	0.3	0.8	0.1	0.1	0.2
2	Grazing	440	1.0		0.1	0.8	0.2	0.6	0.4	0.1	0.4	0.1	0.8	0.7	0.3	0.0	0.3	0.9	0.1	0.1	0.1
3	Moorland	31	1.0	1.0		0.9	0.1	0.9	0.4	0.3	0.5	0.0	0.7	1.0	0.3	0.0	0.1	0.9	0.1	0.0	0.1
4	Woodland	460	1.0	0.8	0.1		0.4	0.6	0.3	0.1	0.4	0.1	0.7	0.7	0.3	0.0	0.3	0.9	0.1	0.1	0.2
5	Plantation	77	1.0	0.9	0.0	0.8		0.4	0.2	0.1	0.5	0.1	0.9	0.7	0.2	0.0	0.2	0.9	0.1	0.1	0.3
6	Uncultivated	291	1.0	0.9	0.1	0.9	0.1		0.4	0.1	0.4	0.1	0.8	0.7	0.3	0.0	0.3	0.9	0.1	0.1	0.1
7	Wasteland	174	1.0	0.9	0.1	0.8	0.1	0.6		0.1	0.3	0.2	0.8	0.7	0.3	0.1	0.3	0.9	0.2	0.1	0.2
8	Tidal	45	1.0	0.9	0.2	0.9	0.1	0.8	0.4		0.5	0.1	0.6	0.8	0.2	0.0	0.2	0.9	0.2	0.1	0.0
9	Setaside	204	1.0	0.9	0.1	0.8	0.2	0.6	0.3	0.1		0.1	0.8	0.8	0.2	0.0	0.2	0.9	0.1	0.1	0.1
10	Amenity	66	1.0	1.0	0.0	0.9	0.2	0.6	0.6	0.1	0.3		0.9	0.7	0.2	0.1	0.6	0.9	0.2	0.1	0.2
11	Arterial road	449	1.0	0.8	0.1	0.8	0.2	0.5	0.3	0.1	0.4	0.1		0.6	0.3	0.0	0.3	0.9	0.1	0.1	0.2
12	Running water	380	1.0	0.9	0.1	0.8	0.1	0.6	0.3	0.1	0.4	0.1	0.8		0.3	0.1	0.3	0.9	0.2	0.2	0.1
13	Standing water	155	1.0	0.7	0.1	0.8	0.1	0.5	0.3	0.1	0.3	0.1	0.8	0.7		0.1	0.3	0.9	0.2	0.2	0.2
14	Horticulture	20	1.0	0.8	0.0	0.9	0.1	0.5	0.6	0.1	0.4	0.4	0.6	0.9	0.5		0.3	1.0	0.3	0.0	0.4
15	Built-up area	152	1.0	0.8	0.0	0.8	0.1	0.5	0.4	0.1	0.3	0.3	0.9	0.7	0.3	0.0		0.9	0.2	0.2	0.1
16	Farm buildings	516	1.0	0.8	0.1	0.8	0.1	0.5	0.3	0.1	0.4	0.1	0.8	0.7	0.3	0.0	0.3		0.1	0.1	0.2
17	Railway	74	1.0	0.8	0.0	0.7	0.1	0.5	0.4	0.1	0.4	0.2	0.8	0.8	0.3	0.1	0.5	0.9		0.2	0.0
18	Disused railway	71	1.0	0.9	0.0	0.9	0.1	0.5	0.3	0.1	0.4	0.1	0.8	0.9	0.5	0.0	0.4	0.9	0.2		0.1
19	Shelter belt	93	1.0	0.7	0.0	0.8	0.2	0.4	0.4	0.0	0.2	0.1	0.8	0.5	0.3	0.1	0.2	0.9	0.0	0.1	

Aspect

The highest mean AI for bird cherry - oat aphid was in fields of south-westerly aspect and for grain aphid in fields of southerly or south-easterly aspect (Table 19). A χ^2 test for association between aspect and frequency of infection by the two aphid species found no significant effects.

Converted to figures for aspect on nearest cardinal compass points (Table 19a), the Aphid Index was three times higher for fields facing west than for fields facing east and 1.4 times higher for fields facing south than those facing north.

Table 19. The relationship of field aspect with Aphid Index and frequency of infestation.

Aspect	n	Mean aphid index			No. of fields infested		
		Aphids	Bird cherry - oat aphid	Grain aphid	Aphids	Bird cherry - oat aphid	Grain aphid
Flat	199	5.89	3.05	2.08	98	76	69
N	33	4.33	3.03	1.00	12	9	6
NE	43	4.07	2.21	1.40	21	17	11
E	22	6.59	3.95	1.91	10	8	5
SE	54	6.02	2.41	2.54	30	20	23
S	52	6.85	3.42	2.92	31	26	28
SW	34	7.82	5.44	2.09	22	18	12
W	27	5.81	3.78	1.67	13	10	9
NW	50	4.44	2.32	1.44	23	17	17
Total	514				260	201	180

Table 19a. Data from Table 19a summarised by cardinal points. Emboldened figures indicate highest values.

Predominant Aspect	n	Mean aphid index			% of fields infested		
		Aphids	Bird cherry-oat aphid	Grain aphid	Aphids	Bird cherry-oat aphid	Grain aphid
N	126	4.3	2.5	1.3	44%	34%	27%
S	140	**6.8**	3.5	**2.6**	**59%**	**46%**	**45%**
E	119	5.4	1.1	2.0	51%	38%	33%
W	111	5.8	**3.6**	1.7	52%	41%	34%

The MAV serotype was more prevalent in east-facing fields and PAV in south-west aspects (Table 20, Fig. 12c,d). The RPV serotype was found to be significantly associated with easterly aspects.

Converted to figures for aspect on cardinal compass points (Table 20a), the incidence of infected fields appeared to be highest for east-facing fields. However, the highest level of PAV occurred in west-facing fields, in accord with the preference observed for bird cherry - oat aphid (Table 19a). The south and east dominance of MAV coincided with the preference of the grain aphid Fig. 12a,b).

Table 20. The relationship of field aspect with mean virus levels and frequency of infection.

Aspect	n	Mean virus				No. of fields infected			
		BYDV	MAV	PAV	RPV	BYDV	MAV	PAV	RPV
Flat	262	1.60	0.88	0.52	0.31	73	40	33	22
N	39	1.51	0.69	0.64	0.62	12	4	4	5
NE	52	0.85	0.29	0.33	0.08	18	7	9	3
E	25	2.04	1.32	0.64	0.28	9	6	5	21
SE	60	1.33	0.60	0.62	0.28	21	13	12	8
S	56	0.91	0.70	0.43	0.32	10	7	8	5
SW	44	2.34	0.18	1.48	0.27	11	3	7	2
W	33	0.88	0.09	0.73	0.03	6	3	4	1
NW	52	0.92	0.17	0.50	0.21	17	6	9	6
Total	623					177	89	91	73

Table 20a. Data from Table 20 summarised by cardinal points. Emboldened figures indicate highest values.

Predominant aspect	n	Mean virus				% of fields infected			
		BYDV	MAV	PAV	RPV	BYDV	MAV	PAV	RPV
N	143	1.1	0.4	0.5	0.3	32%	12%	14%	10%
S	160	**1.5**	0.5	0.4	0.3	26%	14%	17%	9%
E	137	1.3	**0.6**	0.5	0.2	**35%**	**19%**	**19%**	**23%**
W	129	1.4	0.2	**0.9**	0.2	26%	9%	16%	7%

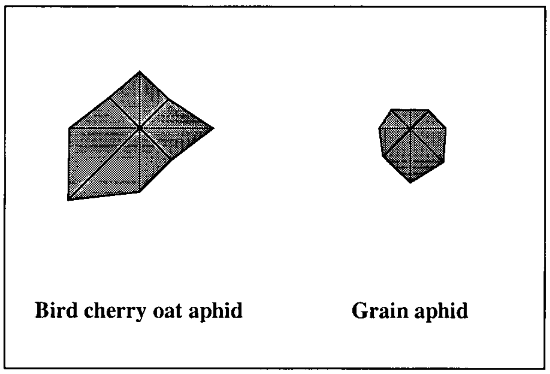


Figure XX. Aphid "rose", based on mean aphid index (Table 19). North is at top.

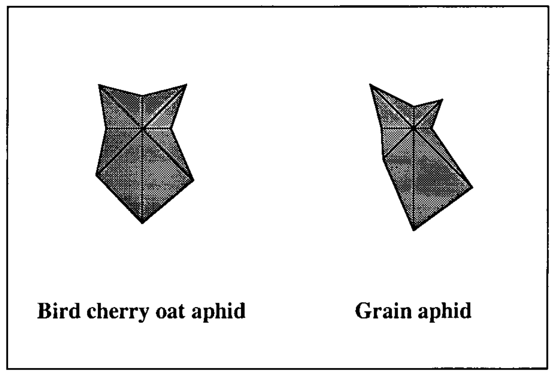


Figure XX. Aphid "rose", based on percentage of fields infested (Table 19).

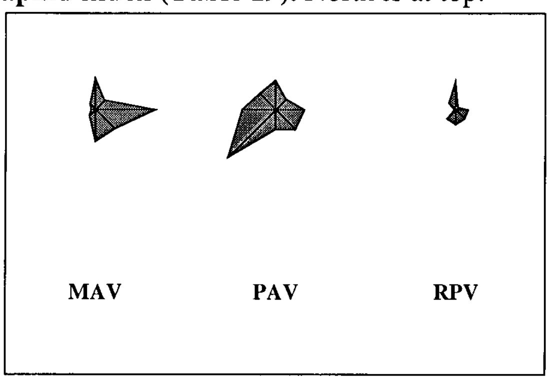


Figure XX. Virus "rose", based on mean virus levels (Table 20).

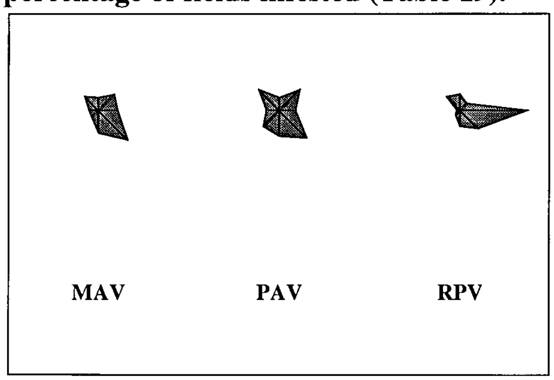


Figure XX. Virus "rose", based on percentages of fields with infected samples (Table 20).

Field size

There was no significant linear relationship between field size and numbers of bird cherry - oat aphid and a weak, negative relationship with numbers of grain aphid. However, the distribution of aphid numbers with respect to field size (Table 21) indicated that small fields and the largest fields had low aphid numbers, and that there was an "optimum" size range for high aphid numbers. This could be interpreted on the basis that aphid numbers were depressed in the largest fields, as these were mainly in intensive arable areas least prone to aphid attack.

Table 21. Mean values for bird cherry - oat aphid, grain aphid and BYDV for seven categories of field size.

Field size	n	Bird cherry - oat aphid	Grain aphid	Total BYDV
< 1 ha	18	0.12	0.29	0.65
1-1.99	13	0.77	0.31	0.23
2-3.99	69	1.89	1.20	1.68
4-7.99	191	1.58	1.02	1.87
8-15.99	226	1.31	0.84	1.32
16-31	84	0.98	0.63	1.00
32+	22	0.45	0.27	0.68

Regression of total BYDV infection against field size indicated no significant linear relationship ($P = 0.95$ using an F test). As with aphids the distribution of infection with respect to field size indicated that small fields and the largest fields had least and that there was an "optimum" size range for infection. This could be interpreted on the basis that virus transmission was depressed in the largest fields, as these were in intensive arable areas less prone to attack by viruliferous aphids.

Soil tilth and texture

Data on seedbed tilth were divided into categories for 320 sites, the remaining fields being reported as varying from one part to another. Tilth was categorised as: capped soil, fine tilth, many peds > 2 cm, many peds > 5 cm. Aphid numbers were lower in fields with a capped soil, especially grain aphid (Table 22). The difference, however, was not significant (for grain aphid P = 0.09). Only 17 sites were in the capped category. No significant differences were found for virus incidence, but MAV was more prevalent in the 'fine tilth' category (P = 0.06) and PAV was more prevalent in the 'small peds' category (P = 0.49).

Soil texture data were available for 451 sites. Texture had been recorded in 11 categories which were regrouped into four classes:

sandy	sand, loamy sand
loam	sandy loam, sandy silt loam, silt loam
clay loam	clay loam, sandy clay loam, silty clay loam
clay	clay, sandy clay, silty clay.

Aphid numbers were highly significantly different across the four classes, with more aphids on the lighter soils (Table 23). Bird cherry - oat aphid was most abundant on loamy soils and least abundant on clay, while grain aphid was most abundant on sandy soils and least abundant on clay loams. All forms of the virus were least abundant on clay, but this difference was not significant.

It had been expected that aphid numbers would be lower where soil tilth was coarse, as such seedbeds would provide more opportunity for some aphids, particularly bird cherry - oat species, to hide. In practice there were no differences of this kind.

On the same basis as for tilth, it might be expected that aphid numbers would be lower on soils with a coarse particle size, but that virus levels would be unaffected. In practice, aphid numbers were significantly higher on sand and loam, and virus levels, though not significantly so, were consistently least on clay soils. This association may relate to the higher risk of BYDV in coastal areas, where light soils predominate.

Table 22. Mean values for incidence of bird cherry - oat aphid, grain aphid and BYDV for four categories of soil tilth, with results of Kruskal-Wallis tests.

Tilth	n	Aphids	Bird cherry - oat aphid	Grain aphid	Virus	MAV	PAV	RPV
Capped	17	4.59	3.53	0.59	0.59	0.47	0.06	0.06
Fine	160	7.43	3.87	2.84	1.72	1.11	0.46	0.38
Small peds	89	7.96	3.92	2.74	1.91	0.73	1.11	0.62
Large peds	54	7.35	3.91	2.63	1.76	0.30	0.80	0.30
	K	3.40	2.0	6.46	0.41	7.32	2.40	1.27
	P	0.33	0.58	0.09	0.94	0.06	0.49	0.74

Table 23. Mean values for incidence of bird cherry - oat aphid, grain aphid and BYDV for four categories of soil type, with results of Kruskal-Wallis tests.

Texture	n	Aphids	Bird cherry – oat aphid	Grain aphid	Virus	MAV	PAV	RPV
Sandy	17	8.76	3.35	4.82	1.88	0.94	0.29	0.18
Loam	106	8.81	4.93	2.89	2.08	1.24	0.66	0.22
Clay loam	271	5.20	3.13	1.53	2.00	0.84	0.99	0.48
Clay	57	6.25	2.11	2.95	0.42	0.11	0.16	0.09
	K	23.67	16.5	22.64	6.49	4.8	2.34	6.25
	p	>0.001	>0.001	>0.001	0.09	0.19	0.50	0.10

Crop weediness

Few crops were scored as having high levels (score 2) for plant trash/weediness. Crops were therefore divided into those with and without either weeds or plant trash. Although none of the individual differences was significant (Kruskal-Wallis tests), means for aphid and virus levels were consistently higher in the weedy crops (Table 24). They were particularly high (x1.9) for the incidence of MAV and RPV.

Table 24. Mean values for incidence of bird cherry – oat aphid, grain aphid and BYDV for two categories of plant trash/weediness.

Score	n	Bird cherry-oat aphid	Grain aphid	MAV	PAV	RPV
none	264	1.28	0.74	0.47	0.52	0.47
some	358	1.48	1.05	0.88	0.69	0.88
multiplication factor		1.2	1.4	1.9	1.3	1.9

Field location

Altitude was found not to have any significant effect on the incidence of aphids or of virus, except for a weak negative correlation with MAV. The altitude range was from sea level to 250 metres AMSL.

Longitude was not significantly correlated with either aphid index or virus incidence, but there was a strong positive correlation between the index of grain aphid and latitude. Bird cherry - oat aphid was most abundant at lower latitudes, about 50°, with a second peak at about 54°, which includes northern England, south-west Scotland and Northern Ireland.

There was more virus in crops closer to the sea.

Previous cropping

Data were available on the previous crop for 603 of the fields. These were classed into four categories: cereals (351), other arable (179), grass (41) and setaside (32). A χ^2 analysis of the frequency of BYDV in the four categories (Table 25) found no significant effect of previous crop. The frequency of aphids was somewhat greater in crops following cereals or other arable crops (Table 25) but this was not significant.

Table 25. Observed and expected frequencies of BYDV and of aphids for four types of previous crop.

	Cereals		Other arable		Grass		Setaside	
	Observed	**Expected**	**Observed**	**Expected**	**Observed**	**Expected**	**Observed**	**Expected**
Virus present	102	100.7	46	51.4	13	11.8	12	9.2
Virus absent	249	250.3	133	127.6	28	29.2	20	22.8
Aphids present	166	153.7	59	68.0	15	15.6	11	13.6
Aphids absent	139	151.3	76	67.0	16	15.4	16	13.4

Use of Linear Modelling

A generalised linear model (GLIM, see Crawley, 1993) was developed to explain the incidence of virus in total or by serotype on the basis of complete data sets for 593 sites. The incidence of aphids was not used in this analysis as the investigation was concerned with the extent to which field characteristics could be used alone to predict the risk.

The most significant factors associated with virus incidence were sowing date, crop type, aspect, distance to the sea and the amount of arable land use in the area (Table 26). Crop type (whether barley or wheat) was only significant for the MAV serotype, and then less so than aspect and sowing date. There was more virus in early sown crops, in crops closer to the sea, and in crops where arable was not the dominant surrounding land use. MAV was more frequent in fields of easterly aspect and PAV in fields of south-westerly aspect.

Table 26. Major factors associated with infection by BYDV.

Strain	Factor	Change in deviance	F	P	Comments
All virus	Sowing date	553.4	29.91	<0.01	more BYDV in earlier-sown crops
	Distance to sea	178.8	9.90	<0.01	more BYDV closer to sea
	Arable land	177.3	9.51	<0.01	more BYDV if arable land absent, least BYDV if arable dominant
	Aspect	134.3	7.46	<0.01	more BYDV in E and SW aspects
	Arterial road	87.38	4.68	<0.05	more BYDV if road absent
MAV	Sowing date	173.3	25.48	<0.01	more MAV in earlier-sown crops
	Aspect	101.9	14.98	<0.01	more MAV in E aspects
	Moorland	41.34	6.08	<0.05	more MAV if moorland present
	Crop type	39.34	5.78	<0.05	more MAV in barley
	Distance to sea	30.24	4.45	<0.05	more MAV closer to sea
	Tidal area	26.29	3.87	<0.05	more MAV if tidal area present
PAV	Sowing date	173.0	26.62	<0.01	more PAV in early sown crops
	Arable land	115.5	17.80	<0.01	more PAV if arable absent, least if arable dominant
	Distance to sea	49.10	7.55	<0.01	more PAV closer to sea
	Aspect	30.67	4.38	<0.05	more PAV in SW aspects
RPV	Arable land	35.00	14.0	<0.01	more RPV if arable present but not dominant
	Distance to sea	22.03	8.81	<0.01	more RPV closer to sea
	Aspect	17.77	7.11	<0.01	most RPV in N, least in W aspects
	Grazing pasture	14.46	5.78	<0.01	more RPV if grazing dominant
	Urban areas	12.24	4.90	<0.05	more RPV if urban area absent
	Tidal area	9.81	3.92	<0.05	more RPV if tidal area present

Discussion and implications for modelling virus spread

Large scale surveys of this kind are both rewarding and frustrating. In reviewing the results of such surveys one should:

- test that well established ideas are supported by the data;
- check for new insights as the basis for further investigation;
- accept a greater risk of Type 1 errors (false positives - ie errors likely to result in unnecessary spraying) than Type 2 (false negatives - ie errors likely to result in spraying not be done when it should have been) by reducing test sensitivity;
- be aware that later investigation may reveal further insights.

Testing well established ideas

In the present case, well established ideas and perceptions that can be tested are:

- the known incidence of serious BYDV outbreaks in coastal regions;
- the perceived difficulty of detecting aphids in dull weather conditions;
- yellowing is a good indicator of BYDV incidence;
- the association of aphid abundance with virus incidence;
- the association of MAV with the grain aphid, and the association of PAV and RPV with the bird cherry – oat aphid;
- the association of viruses, in particular MAV, with stubble regrowth and otherwise weedy crops;
- the perceived importance of date of planting on virus incidence;
- the association of BYDV with barley more than wheat;
- the association of BYDV with the abundance of grass, and the perceived importance of setaside.

Accumulated results for all three years (Figure 7a) indicate that the risk associated with coastal crops is largely `Atlantic', from Kent to Northern Ireland and Ayrshire., but also in Berwickshire. Coastal crops on the eastern English coast, including most of East Anglia, are not generally at risk. Inland crops are at much lower risk than coastal crops, but outbreaks occurred north of London in 1997/8 (Fig. 7d), mainly MAV (Fig. 8d). This picture fits well with the map of high BYDV risk much used by ADAS in the 1980s. Figure 7a does, however, emphasise that other factors may also be important in causing localised outbreaks away from the main areas of high risk.

Farmers and crop walkers are advised to confirm the presence of aphids before taking action. This advice usually includes the need to inspect on a sunny day. The present data indicate (Table 8) that this advice should be modified to specify a warm, sunny day as opposed to the bright conditions more usually associated with overnight frost in winter. In fact, overcast conditions associated with rain appeared to be more conducive to the detection of aphids than bright days in general.

There was a good relationship between the yellowing of the crops and the levels of virus detected by ELISA (Table 11).

Aphid incidence and virus infection were strongly correlated (Table 12), as were incidences of the two main aphid species and the two main strains of virus. The strongest species-serotype relationships were bird cherry - oat aphid with PAV and grain aphid with MAV. RPV incidence was not related to the incidence of either species, probably because of its spasmodic detection.

Although individual comparisons yielded no significant results, there were consistently more aphids and more virus associated with weedy as opposed to clean crops (Table 24). This difference was most marked for MAV and RPV, which have been shown (Henry *et al.* 1993) to be the main serotypes associated with grasses in field margins. Henry et al. (1993) also noted the predominance of MAV in stubble regrowth in England, as opposed to PAV in France. Masterman et al. (1994) noted local variations in the dominant serotype in infection of *Poa annua*, an important weed of cereal stubbles, with MAV predominant in the autumn. The present results are thus consistent with earlier findings.

Sowing date was identified by linear modelling as the most useful explanatory variable. Differences between wheat and barley largely owed to differences in planting date (median dates late September for barley and early October for wheat).

The association of BYDV with surrounding land use was not as obvious as expected (Table

17), but there was significantly more virus in areas where arable land was merely present, as opposed to being dominant. Linear modelling of total virus (Table 26) selected the scarcity of arable land as the third most important variable. Aphid infestation was clearly associated with non-arable usage (Table 16).

The most startling departure from expectation was the absence of influence of setaside on virus levels (Table 17). Setaside was well represented in the data-set, being present in the vicinity of 203 of the 614 fields analysed for this attribute. Aphid numbers in general (but not individual species) were higher near to setaside.

Linear modelling approach

The linear modelling approach, like other multivariate techniques, ensures that the factors measured are placed in a hierarchy of importance. One should be aware that:

- the analysis can only select from the factors actually measured;
- some factors may act as surrogates for others, i.e. correlation does not necessarily indicate causation;
- the hierarchy may vary from one region to another.

Regional variations are usually taken into account in the linear modelling process but surrogacy must be interpreted by the user.

New insights and sensitivity

If the insights are merely used as the basis for discussion of further work, then the sensitivity of testing should not be an issue. If, however, they are used to modify the forecasting model at the field-by-field level then sensitivity becomes important. Taking the level of significance for acceptance to the 0.01% level is one approach, but we have preferred to use non-parametric tests wherever possible as such tests make no assumptions about the distributions of the data.

The susceptibility and tolerance to aphids and to virus infection were distinct. The wheat cultivar Reaper and the barley cultivars Fighter, Intro and Regina all had relatively high incidences of virus but only Fighter had high aphid numbers. The co-occurrence of the two main aphid species appeared to be higher than might be expected on the basis of sowing date or regional differences alone, i.e. it appeared that some cultivars were susceptible or resistant to aphids as such, not to a particular species.

Given the known sensitivity of aphids to slight variations in temperature, it is surprising that so little has been done to identify the importance of field aspect. The association of levels of bird cherry - oat aphid and PAV with field facing south-west can be interpreted in various ways. The prevailing wind over much the area is from the south-west, the main sources of viruliferous aphids are in the south-west extremities of the country, and fields of a south-western aspect benefit from afternoon and evening sun. Grain aphid and MAV (and RPV) were more associated with fields of eastern and southern aspect, indicating greater tolerance of persistent frosts but less tolerance of the severe effects of wind. Stubble regrowth, which has previously been associated with higher levels of MAV in England and PAV in France (Henry *et al.* 1993), may also be favoured by exposure to the south-west. The east-west trend for the two main aphid/virus associations was also detected for 26 barley crops in the west of Scotland in an earlier survey (Masterman *et al.* 1993). Such surveys emphasise the need for more detailed studies of crop microclimates.

The most peculiar association detected was that of virus levels being lower near to arterial roads (Table 17). This was not the case for aphid numbers, which were if anything higher. This association might be rejected as spurious were it not that that same effect for virus was observed near railway lines in use but not those in disuse. With the exception of setaside (see above), field characteristics resulting in uncultivated land or disturbed, weedy ground were generally associated with higher virus levels. Spellerberg (1998) noted that arterial roads could have an impact on biological communities beside them, and he cited artificial lighting, heavy metals, dust, sand, de-icing material and gases as causative factors. The growth of some plants, in particular grasses, can be enhanced near to roadways, whereas others, in particular trees, are injured by exposure to noxious gases. The apparent reduction in virus levels in fields next to arterial roads may be based on real effects, but the logic is far from clear. The table of co-occurrences of land types (Table 18) does not provide an explanation for this phenomenon.

The distribution of effort over the three years of survey was constrained by other commitments in the project, resulting in the greatest number of field surveys being undertaken in the year of lowest BYDV incidence. BYDV incidence was generally low across the three years, but more survey work in 1997/8 would have been more rewarding than the effort associated with 1996/7.

The assembly of such a large database broke new ground in bringing together so many participants for a common goal. Its management was originally through a dedicated package based on Microsoft Access, but interrogation of the data was largely achieved in Excel. These programs are not fully compatible and the statistical routines available in Excel suffer from some faults that only became apparent during this investigation, e.g. incorrect allocation of the rankings essential for the non-parametric tests.

It is recognised that other workers may benefit from having access to the data-base. Long term maintenance of a dedicated website is not currently practicable, but the authors will share the data with others.

Implications for modelling virus spread

Quantitative use in the model requires further development. This will be tackled through an extension to the MAFF project, which supports the modelling programme. Key field characteristics have been identified which increase or decrease the risk of BYDV. If the regional model of incidence indicates low risk, it may be unnecessary to spray regardless of field characteristics. If the regional model indicates high risk, it may be necessary to spray regardless of field characteristics. In cases where the regional model predicts intermediate risk, the information on field characteristics in relation to BYDV incidence will provide a valuable pointer as to the likely value of spraying, even if the data are only used qualitatively.

DEVELOPMENT AND VALIDATION OF A MODEL OF BYDV SPREAD

Introduction

A computer model (Fig. 13) was constructed under MAFF-funded project number CE0410 to simulate the dynamics and behaviour of aphid vectors and the epidemiology of BYDV.

Methods

The model

To represent the complexity of virus epidemiology, an innovative stochastic individual-based model was developed. Data from various published and unpublished sources, and from MAFF- and HGCA-funded studies, were used to derive the mathematical algorithms used in the model. The model has been subjected to continual verification and refinement and a series of field studies described below was done to validate the model at three sites in different parts of the UK. Predictions from the model were compared against the field data for aphid counts and virus incidence. Local data on crop growth, winged aphid numbers and environmental conditions were utilised to drive the model. Full details of the model will be given in the project report to MAFF.

Validation data

Experiments to obtain data against which to validate the model of virus spread were done at Rothamsted, Starcross and Auchincruive during the winter of 1996/1997 and at Rothamsted and Starcross during the winter of 1997/1998.

Four 8m x 8m plots of winter wheat (cv Beaufort) and four of winter barley (cv Puffin) were drilled on the following dates :

Rothamsted	22nd August 1996,	18th August 1997
Starcross	10th September 1996,	10th September 1997
Auchincruive	27th August 1996	

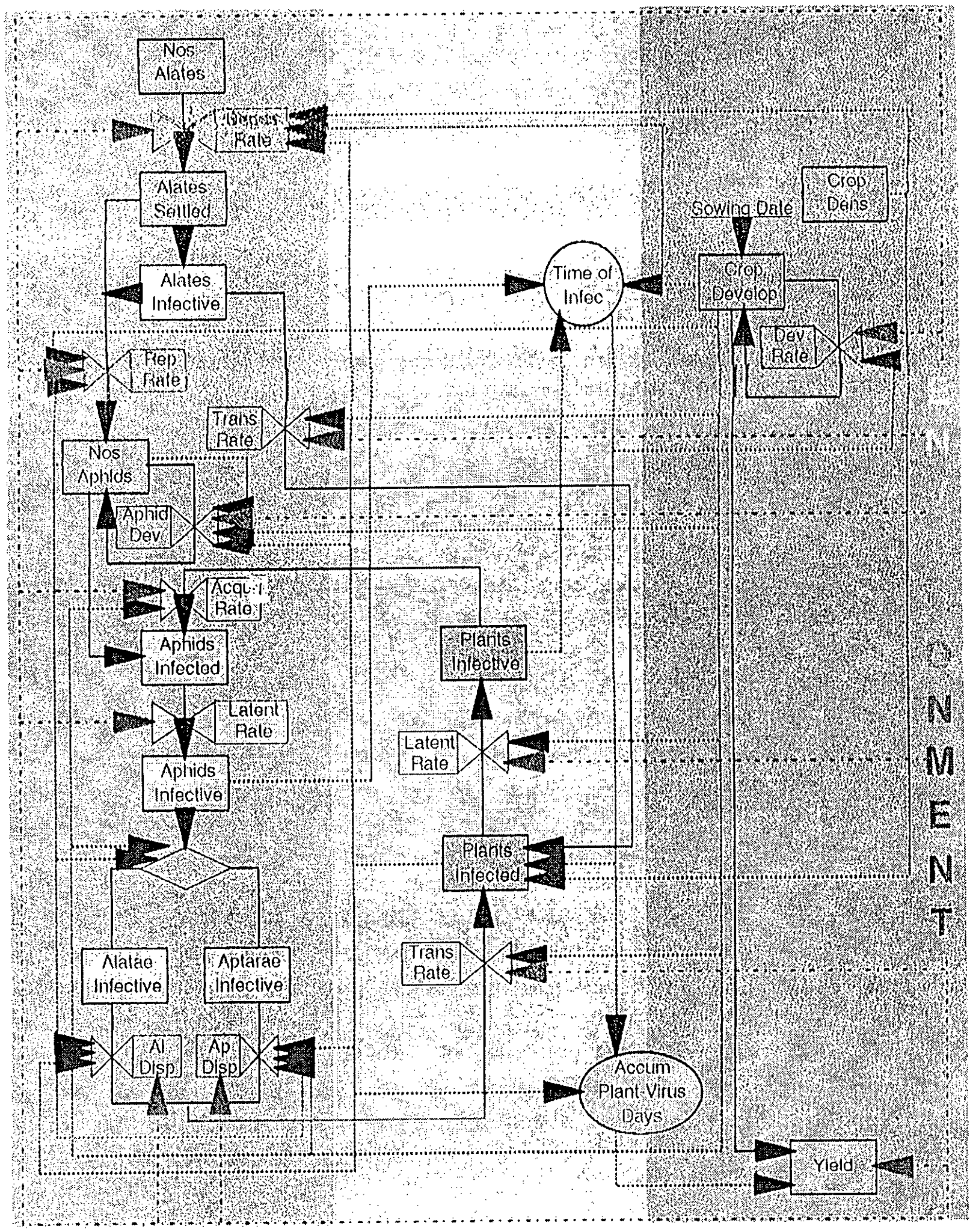


Figure 13. Flow diagram of computer model.

The plots were arranged as four blocks of two, barley and wheat being assigned randomly within the block. Each plot was marked into sixteen 2m x 2m subplots. At Rothamsted in 1996, eight winged viruliferous bird cherry - oat aphids and eight viruliferous grain aphids were released into each subplot soon after full crop emergence. The same was done at Auchincruive using four winged adults and eight nymphs of each of the two aphid species. After one week a subplot from each plot was chosen at random and sampled for aphids. Six 0.5m rows of crop were sampled in each subplot and the numbers of winged adults, wingless adults, first to third instar nymphs and fourth instar nymphs of each aphid species were recorded. Sampled subplots were sprayed with an insecticide (Deltamethrin @ 200 l ha^{-1}) with a hand held spray boom. After one week, the process was repeated on a new subplot within each plot and previously sprayed subplots were resprayed to prevent reinfection. This was repeated at weekly intervals until the end of November and every two to four weeks, depending on conditions, during December, January and February. One subplot per plot was left unsprayed as a control. Numbers of plants sampled on each occasion were recorded and numbers of aphids counted were converted to numbers per plant for assessment against model output. Temperature, rainfall, windpeed and relative humidity were recorded at weather stations within 1km of the trials. In late March/early April, when crops were between growth stages 35 and 41 (Tottman and Broad, 1987), all subplots were assessed visually for BYDV symptoms. A 1.5m x 1.5m quadrat split into 25 squares was placed over the centre of each subplot and a visual score given to each square (Watson and Mulligan, 1960; Doodson and Saunders, 1970). After visual assessment, the youngest fully emerged leaf from the plant nearest to the centre of each quadrat was placed into a labelled bag which was sent to CSL and stored frozen until the leaves were tested for their BYDV content using TAS-ELISA.

Results

Results of the model simulation runs reported here are for bird cherry - oat aphid and all BYDV isolates in barley. Virus incidence as recorded by ELISA results rather than visual symptoms was used in comparison with the model output. Full details for all aphid/virus/crop combinations will be given in the report to MAFF.

Rothamsted 1996/7

Aphid numbers in unsprayed barley plots are shown in Fig. 14a and wheat plots in Fig. 14b. Numbers of bird cherry - oat aphid peaked in early November and were similar in wheat and barley, never exceeding 100 per 12m of crop. Numbers of grain aphid peaked in late October at 23 per 12m of wheat and in early November at 45 per 12m barley.

The model gave an accurate prediction of the number of bird cherry – oat aphid per barley plant throughout the season (Fig. 16a).

Virus incidence measured by visual inspection and by ELISA is shown in Fig. 15. Symptoms in barley (Fig. 15a) peaked at 26% in plots sprayed on 25th November. Unsprayed control plots showed 37% of plants to be infected. ELISA tests were done first on samples from plots sprayed on 17th September, 4th November and 27th January, and on unsprayed control plots. Visual symptoms in wheat (Fig. 15b) peaked at 36% in plots sprayed on 11th November. Unsprayed control plots showed 37% plants to be infected. As all plots of a particular crop species showed similar levels of virus, intermediate samples were not tested as it was considered that they would give similar results. 13 to 16% of wheat plants were infected in each sample and 2% of barley plants.

The model gave an accurate prediction of virus incidence in barley throughout the season (Fig. 16b).

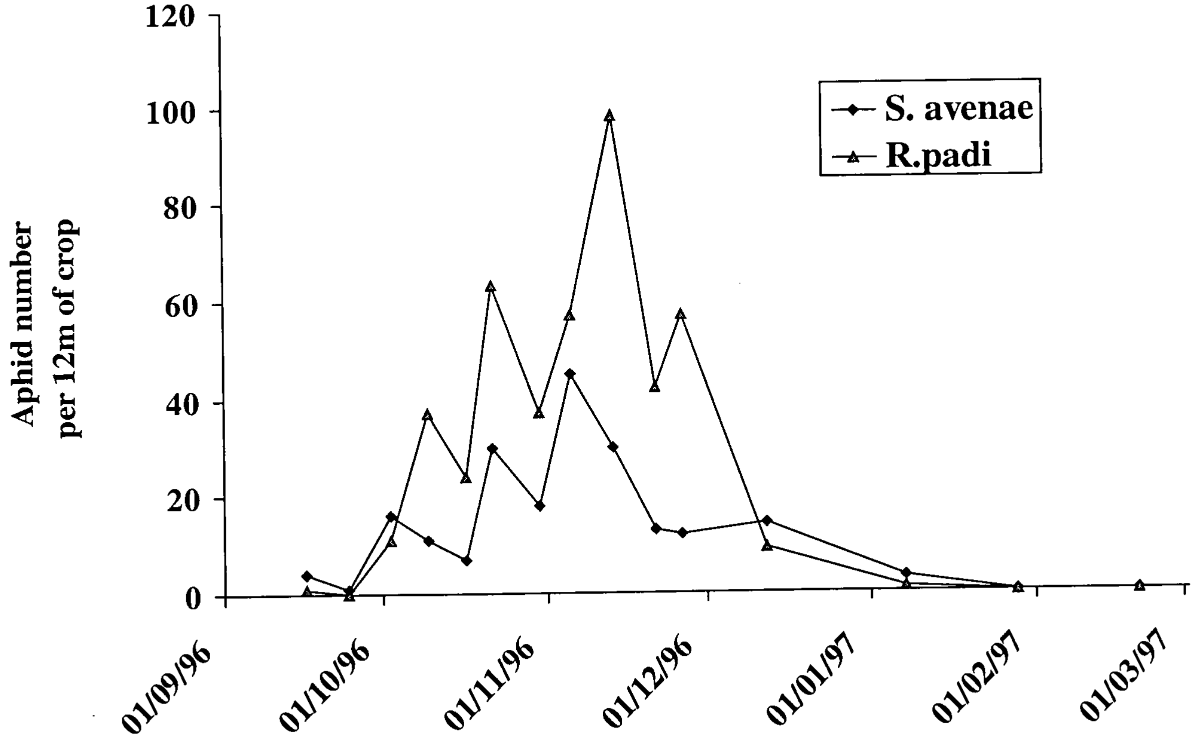


Figure 14a. Aphid numbers in unsprayed barley plots, Rothamsted 1996/7.

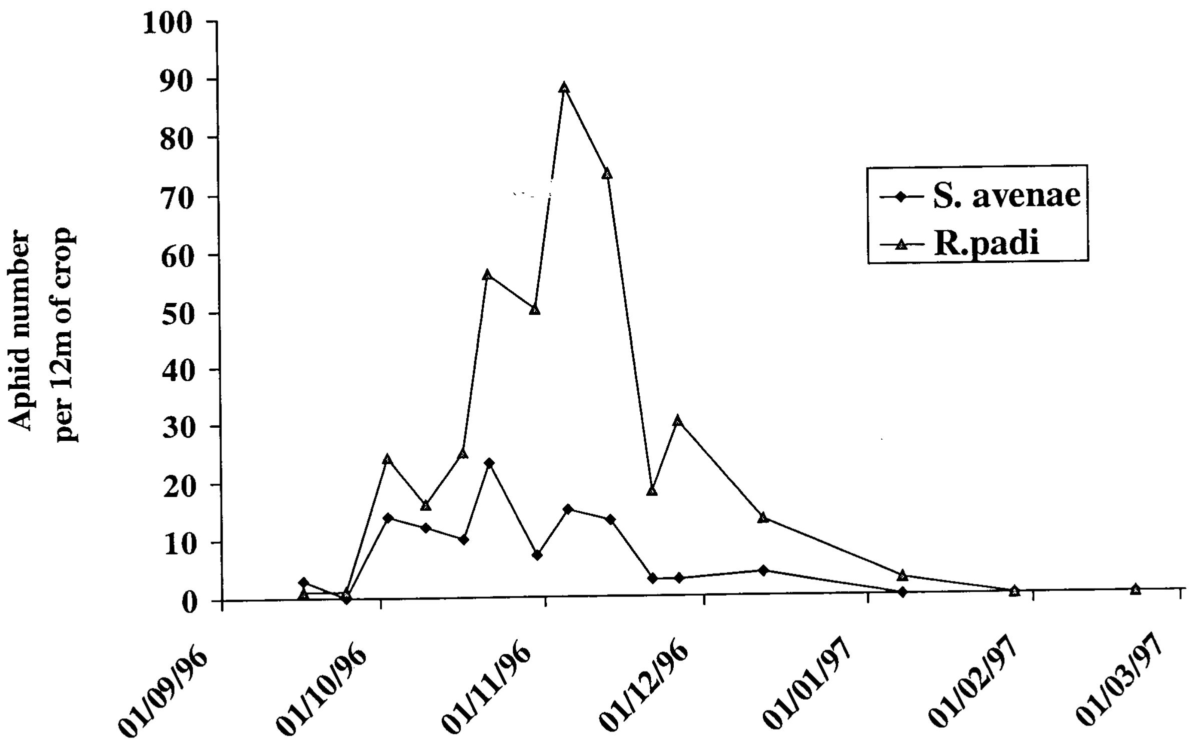


Figure 14b. Aphid numbers in unsprayed wheat plots, Rothamsted 1996/7.

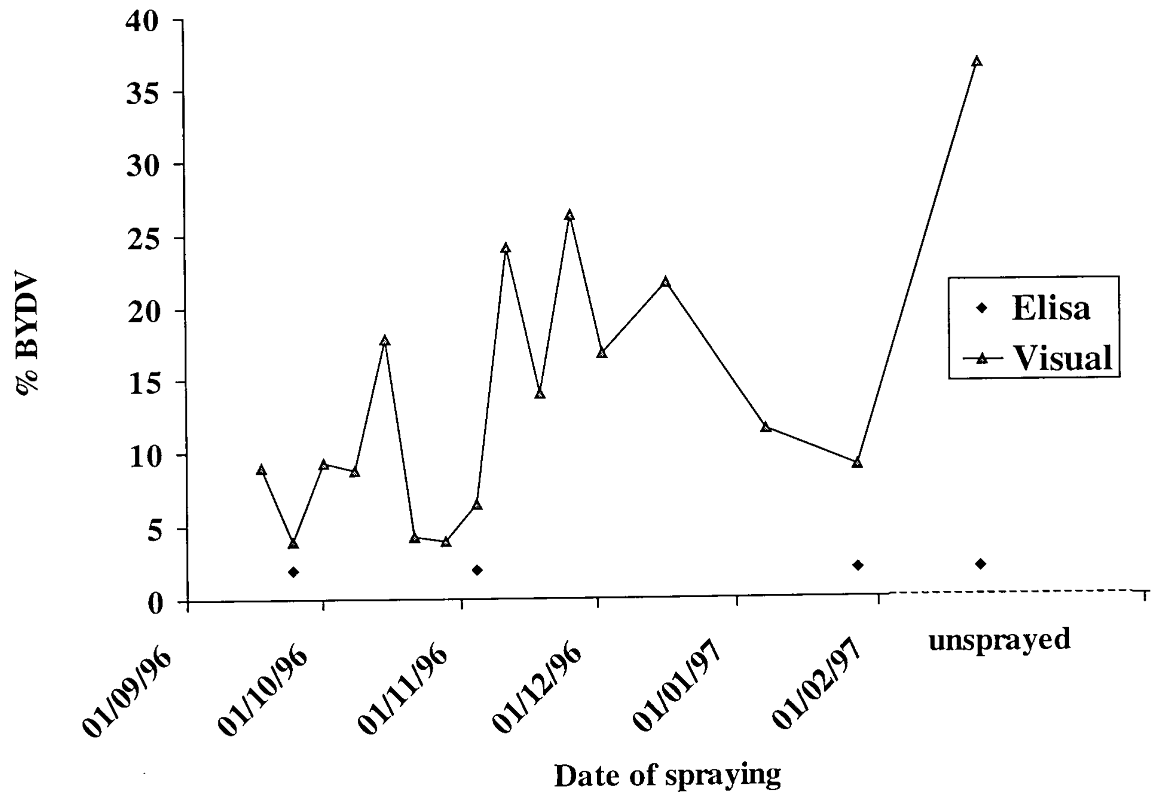


Figure 15a. BYDV incidence in barley plots, Rothamsted 1996/7.

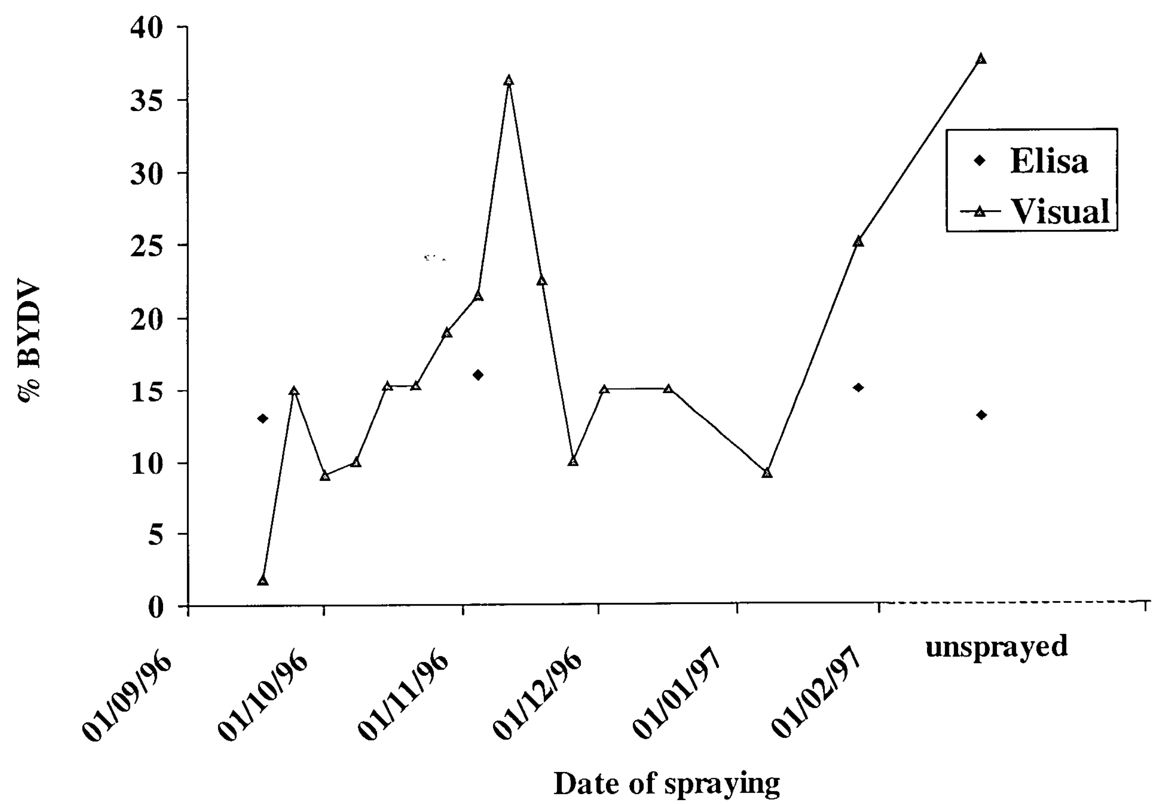


Figure 15b. BYDV incidence in wheat plots, Rothamsted 1996/7.

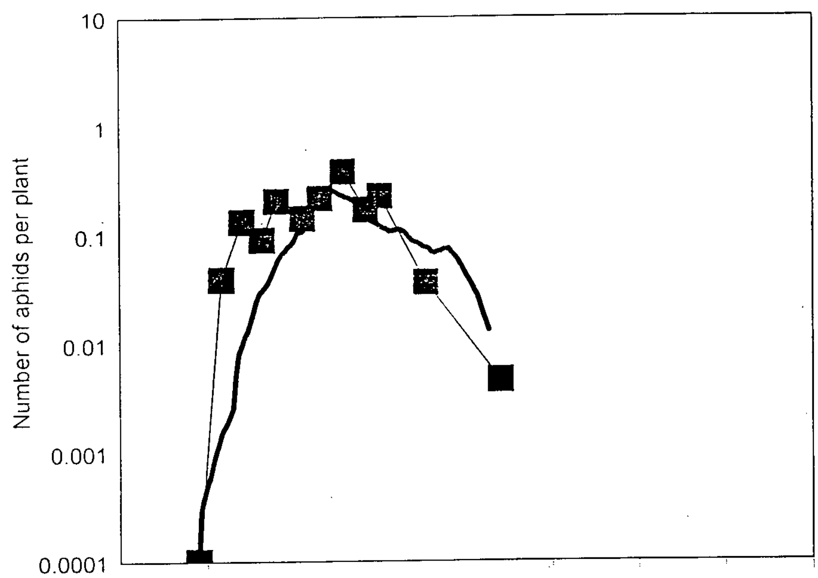
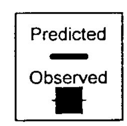


Figure 16a. Predicted vs observed aphid incidence in barley, Rothamsted 1996/7.



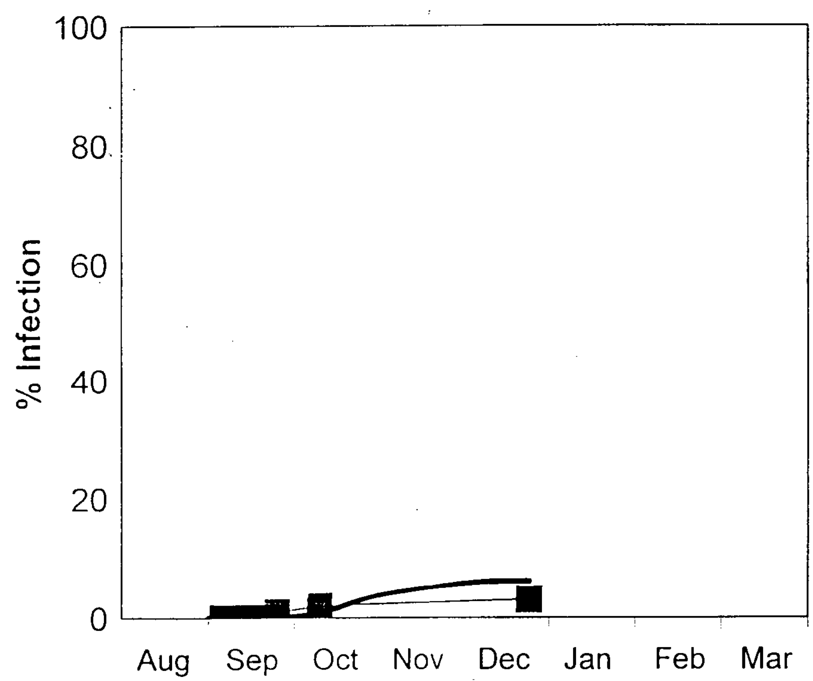


Figure 16b. Predicted vs observed BYDV incidence in barley, Rothamsted 1996/7.

Starcross 1996/7

Aphid numbers in unsprayed barley plots are shown in Fig. 17a and wheat plots in Fig. 17b. Numbers of bird cherry - oat aphid peaked in mid October, were similar in wheat and barley and slightly larger than at Rothamsted. There were very few grain aphids in either crop.

The model predicted the initial and final numbers of bird cherry – oat aphid in barley accurately, but numbers in November and December were lower than predicted (Fig. 19a).

Virus incidence measured by visual inspection and by ELISA is shown in Fig. 18. Visual symptoms peaked in barley (Fig. 18a) at 91% in crops sprayed on 23rd January and ELISA assessment at 43% in crops sprayed on 15th November. Untreated crops had 66% infection according to visual assessment and 40% by ELISA assessment. In wheat (Fig. 18b) visual symptoms peaked at 79% in crops sprayed from 4th December and ELISA assessment at 53% in crops sprayed from 4th November. Untreated crops had 71% infection according to visual assessment and 62% by ELISA assessment.

The model predicted the initial and final virus levels in barley accurately, but incidence in plots spayed in mid November was higher than predicted (Fig. 19b).

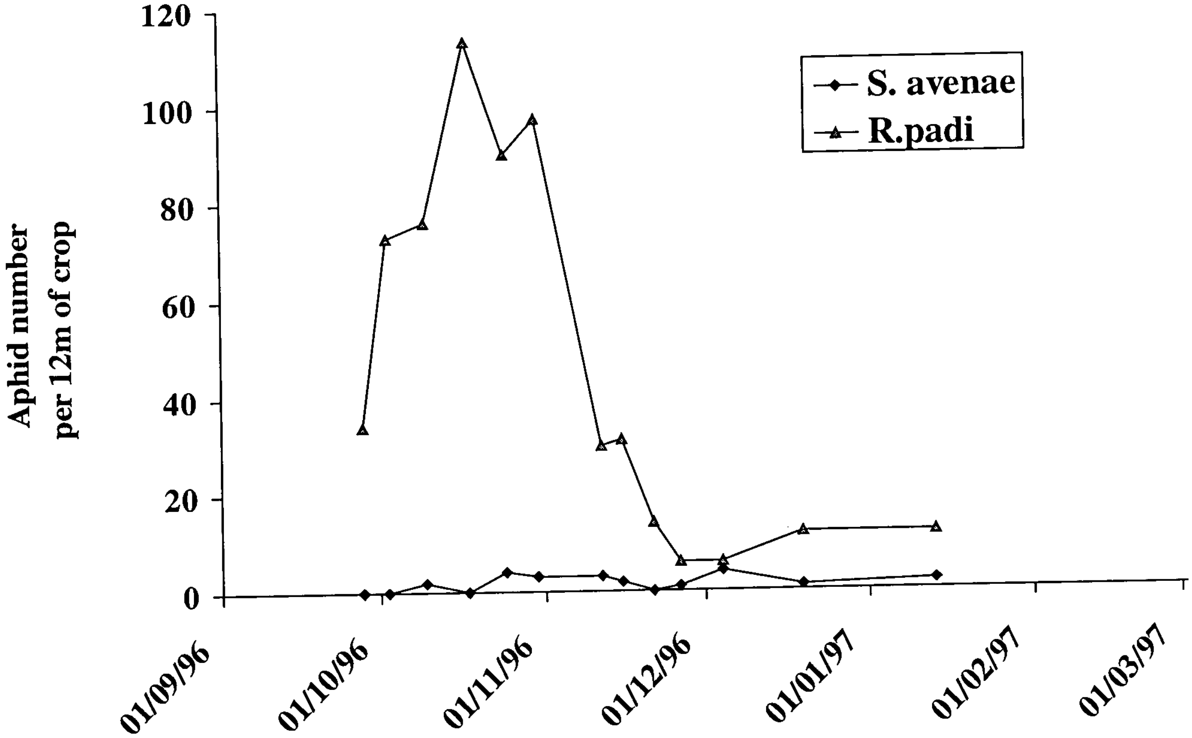


Figure 17a. Aphid numbers in unsprayed barley plots, Starcross 1996/7.

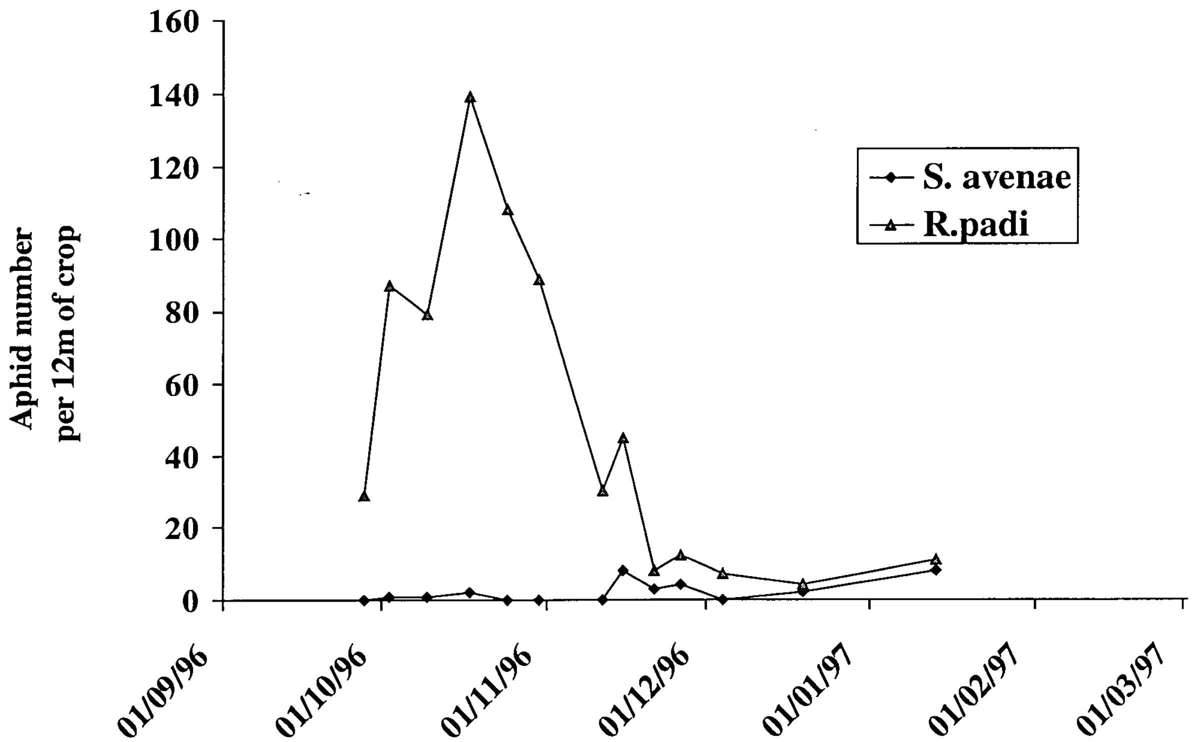


Figure 17b. Aphid numbers in unsprayed wheat plots, Starcross 1996/7.

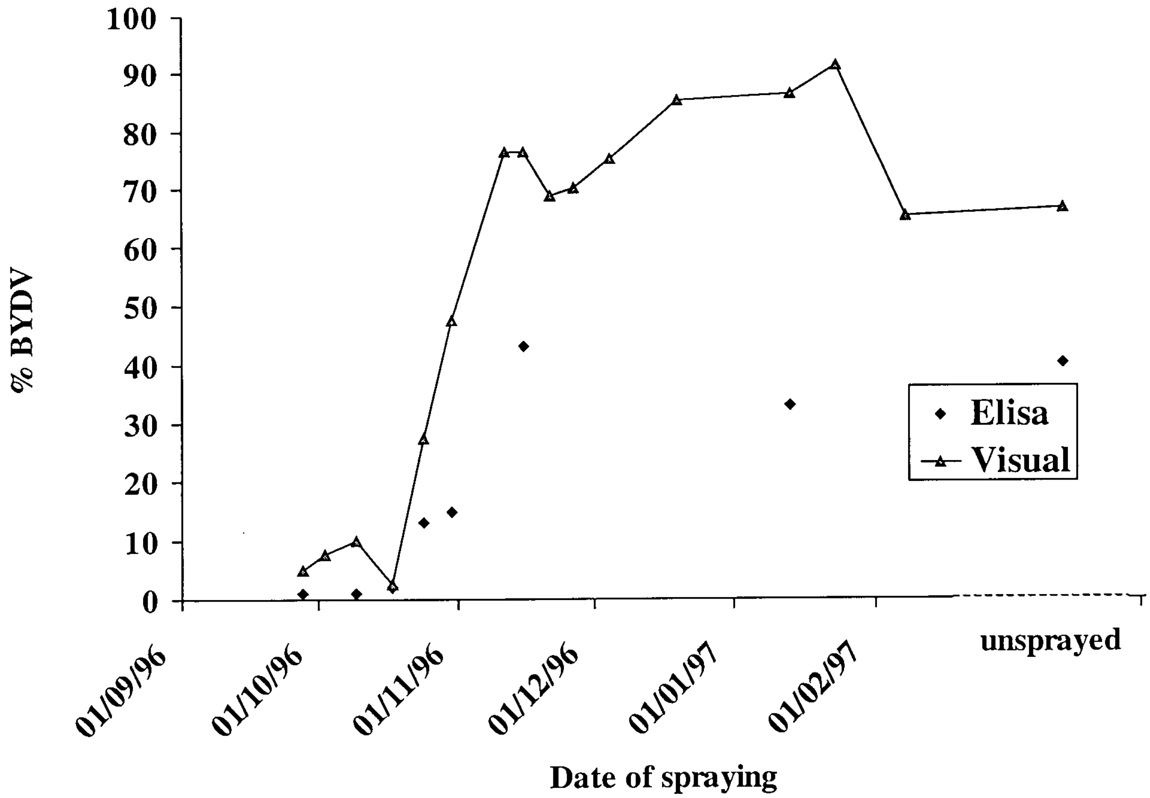


Figure 18a. BYDV incidence in barley plots, Starcross 1996/7.

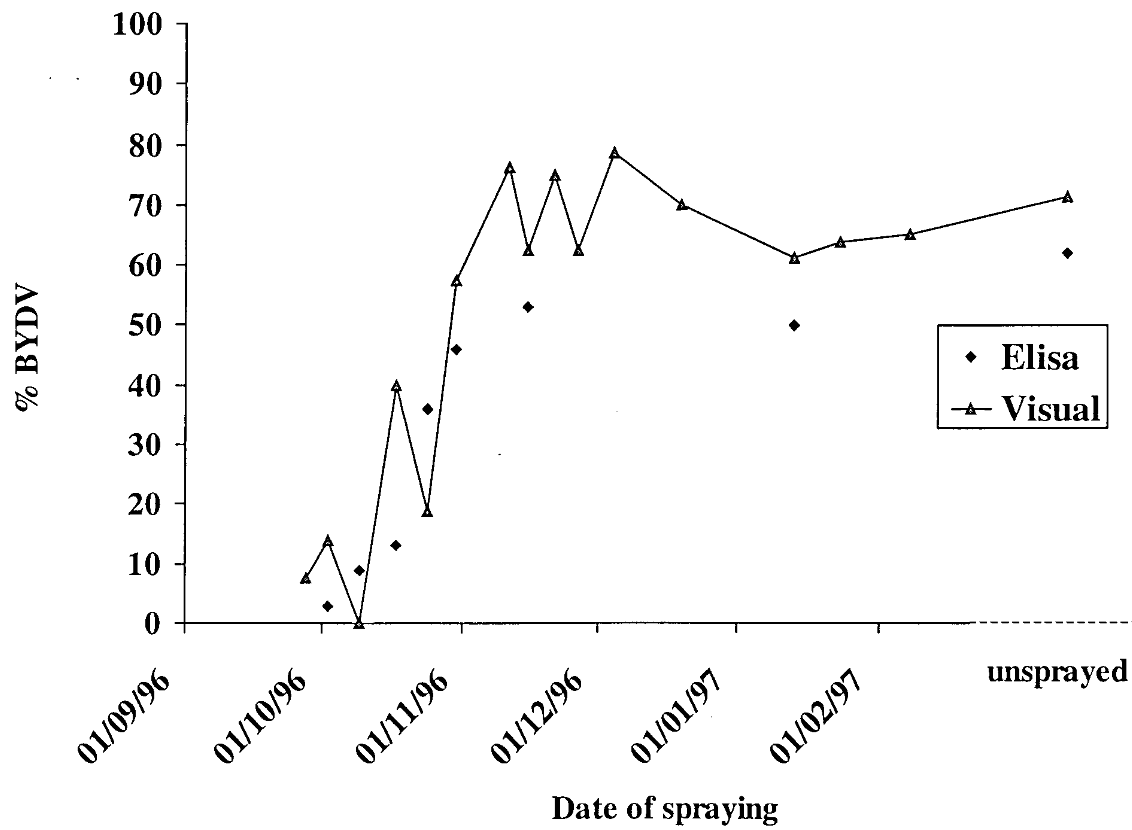


Figure 18b. BYDV incidence in wheat plots, Starcross 1996/7.

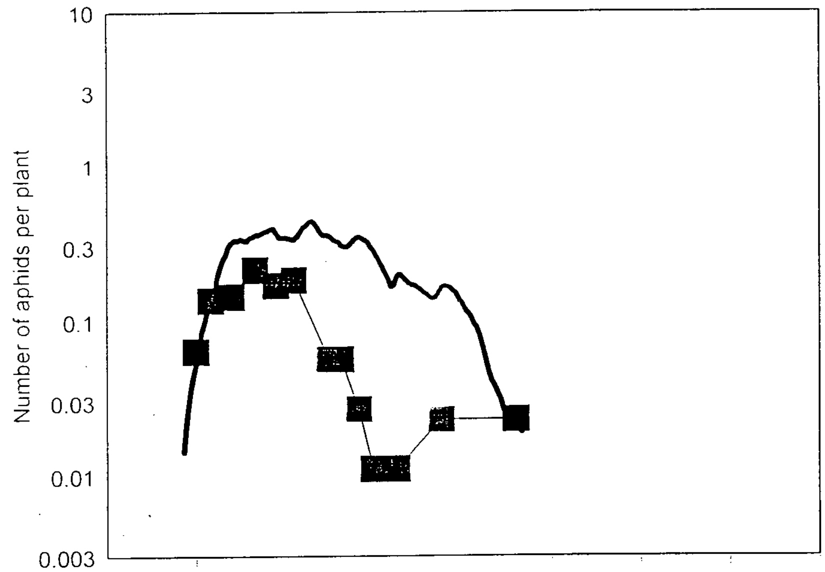


Figure 19a. Predicted vs observed aphid incidence in barley, Starcross 1996/7.

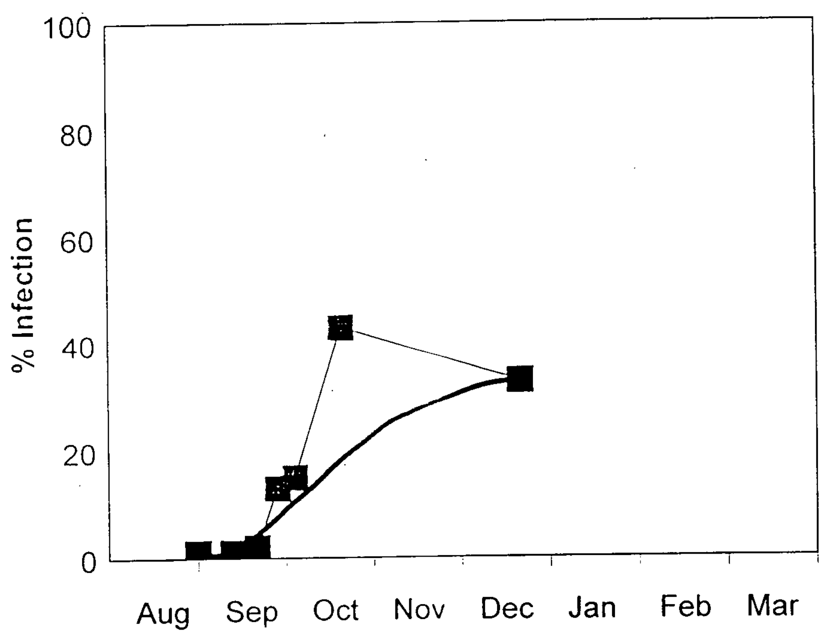


Figure 19b. Predicted vs observed BYDV incidence in barley, Starcross 1996/7.

Auchincruive 1996/7

Aphid numbers in unsprayed barley plots are shown in Fig 20a and wheat plots in Fig 20b. Numbers of bird cherry - oat aphid were very low in both crops. There were about 20 grain aphids per 12m of crop in early samples, but by early October numbers were very low in both crops.

Numbers of bird cherry - oat aphid in barley were considerably lower than predicted by the model throughout the season (Fig. 22a).

Virus incidence measured by visual inspection and by ELISA is shown in Fig. 21. Visual inspection showed infection in barley (Fig. 21a) to peak at 29% in crops sprayed on 28th January. Unsprayed control plots showed 21% infection. Infection in wheat (Fig. 21b) peaked at 12% in plots sprayed on 26th November. Unsprayed control plots showed 18% infection. Elisa testing showed a maximum of 3% barley plants and 4% wheat plants to be infected.

The model accurately predicted virus incidence in barley plots sprayed in mid September and early November, but incidence was lower than predicted in early February (Fig. 22b).

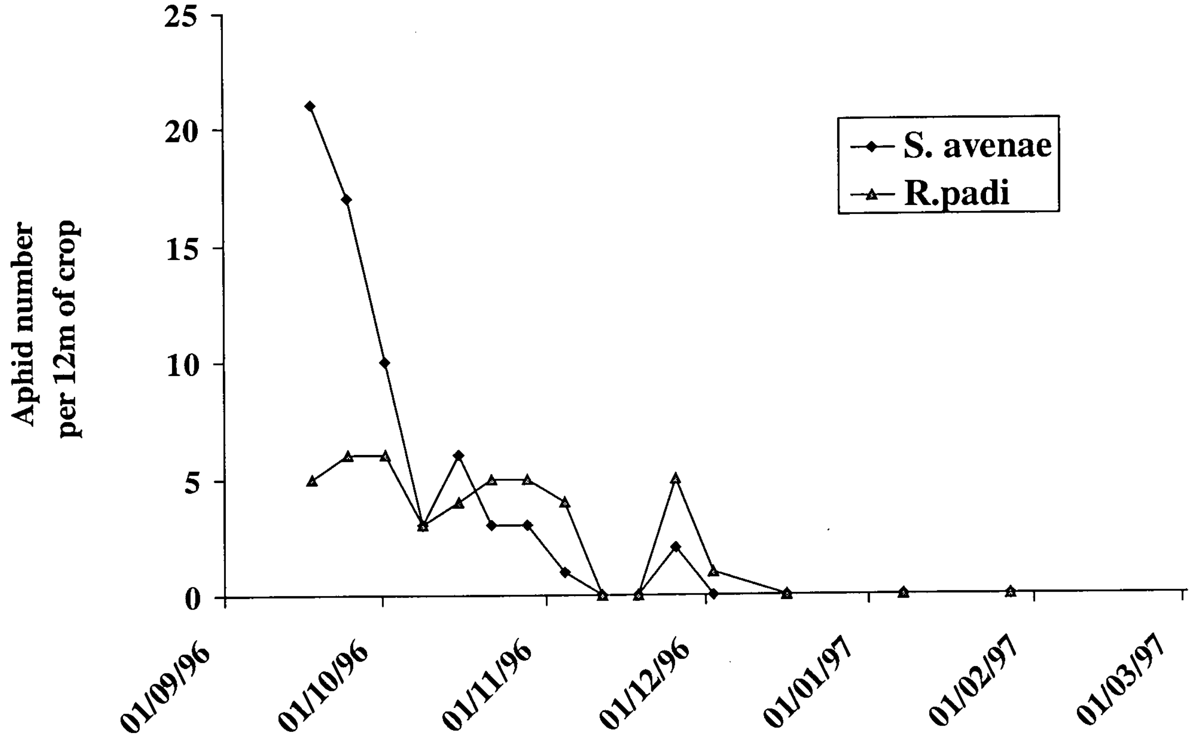


Figure 20a. Aphid numbers in unsprayed barley plots, Auchincruive 1996/7.

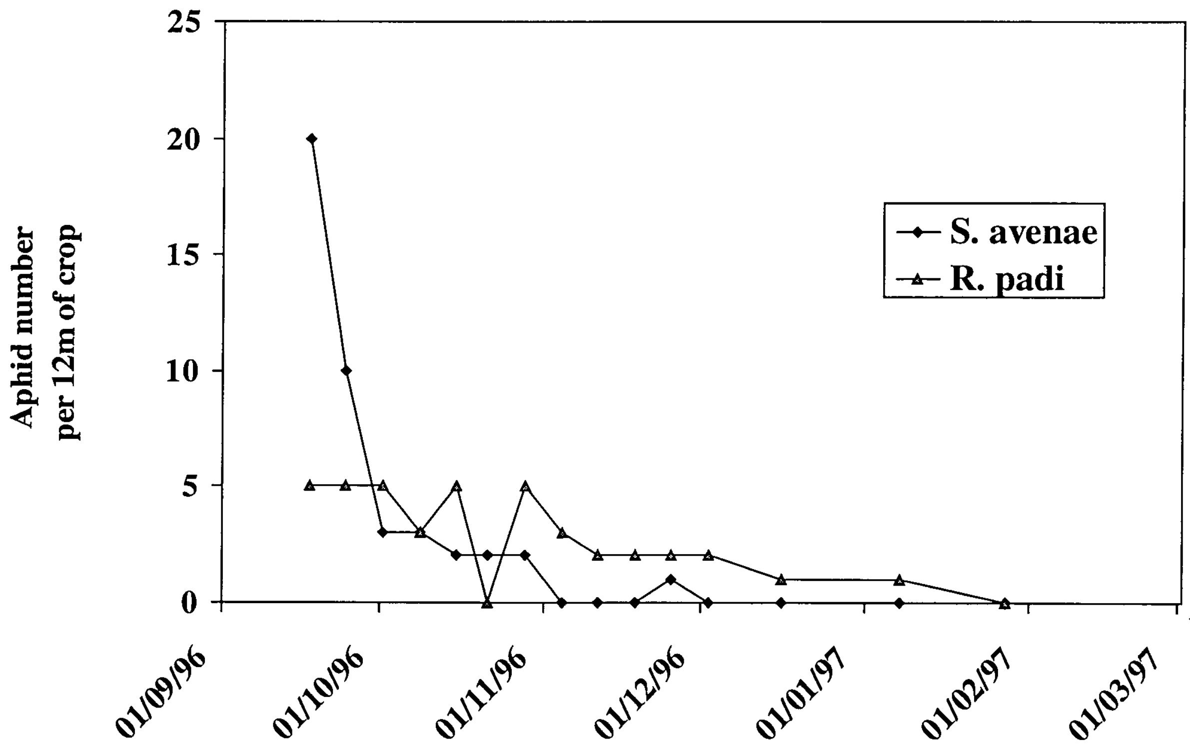


Figure 20b. Aphid numbers in unsprayed wheat plots, Auchincruive 1996/7.

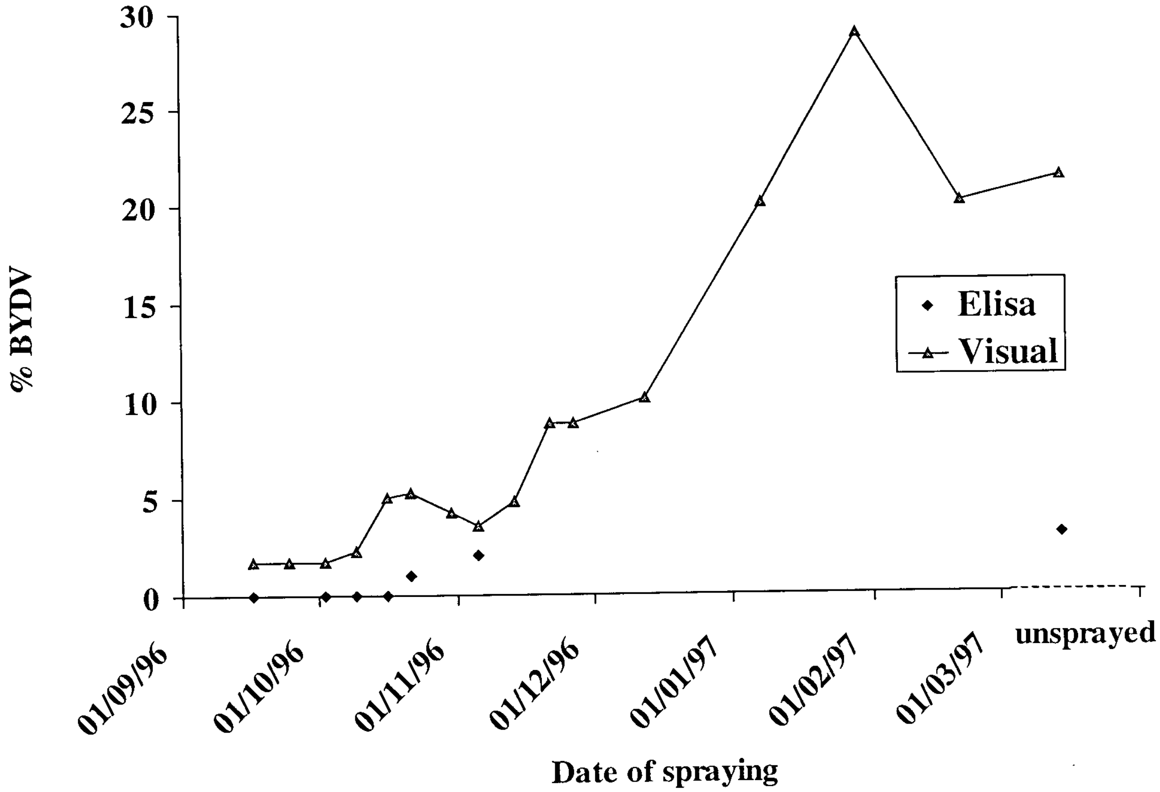


Figure 21a. BYDV incidence in barley plots, Auchincruive 1996/7.

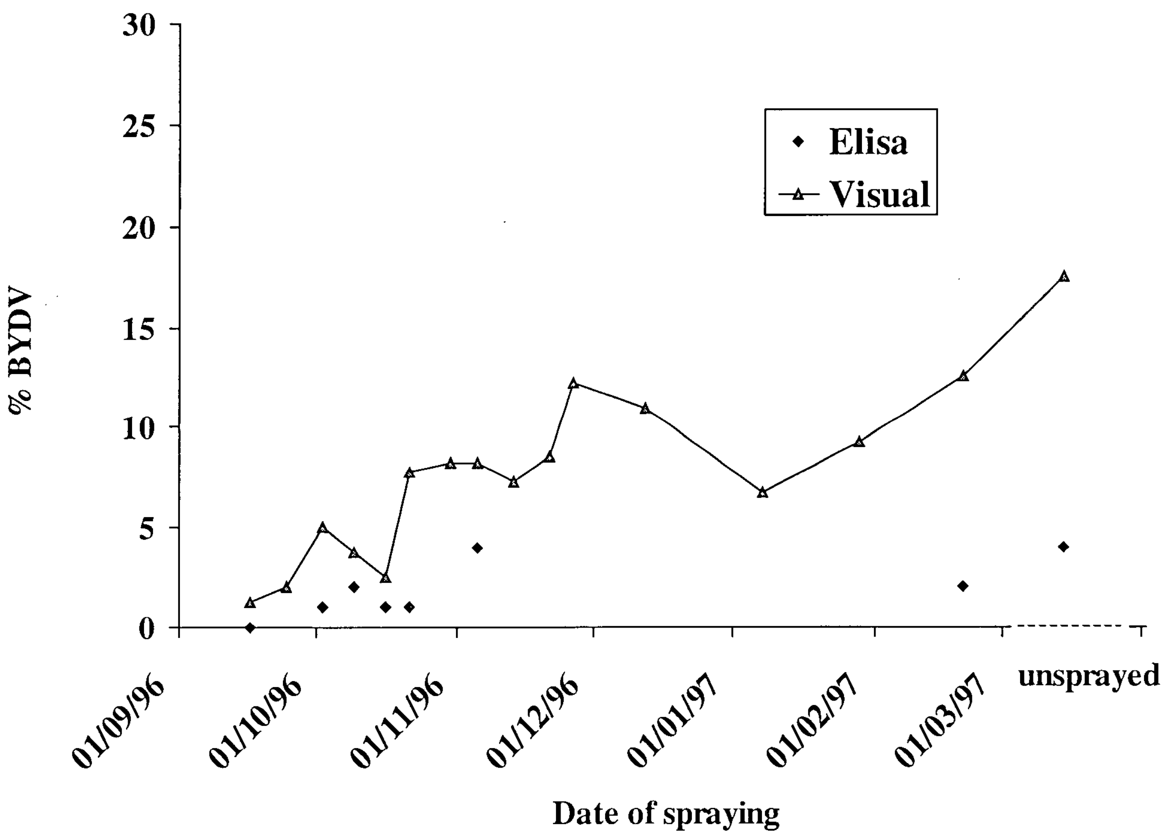


Figure 21b. BYDV incidence in wheat plots, Auchincruive 1996/7.

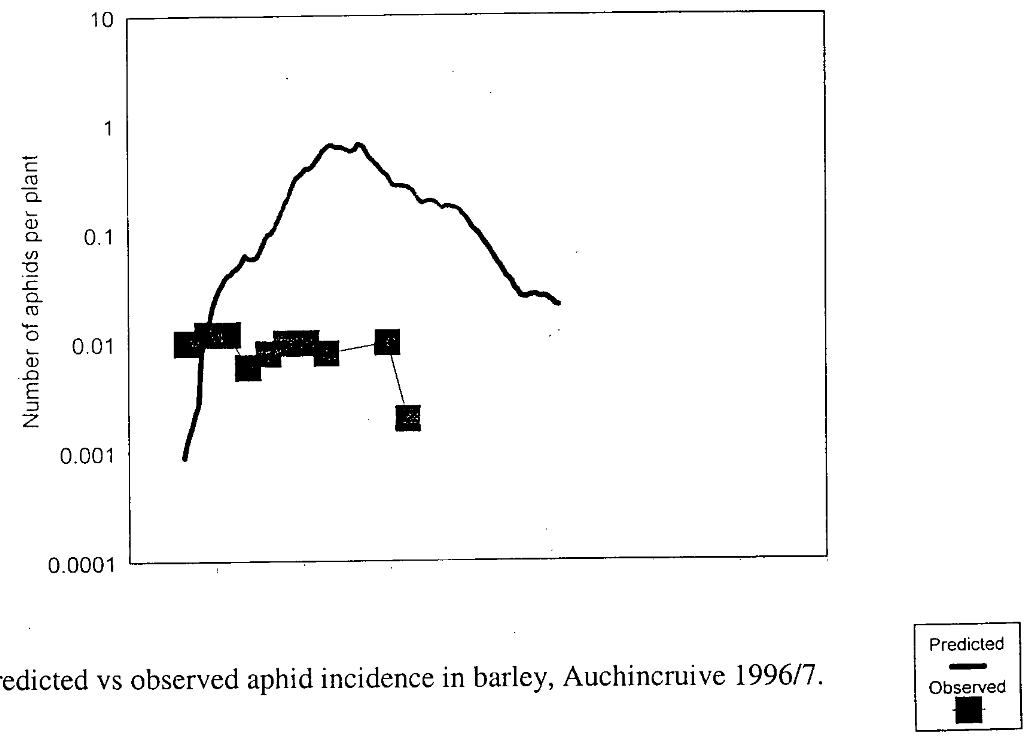


Figure 22a. Predicted vs observed aphid incidence in barley, Auchincruive 1996/7.

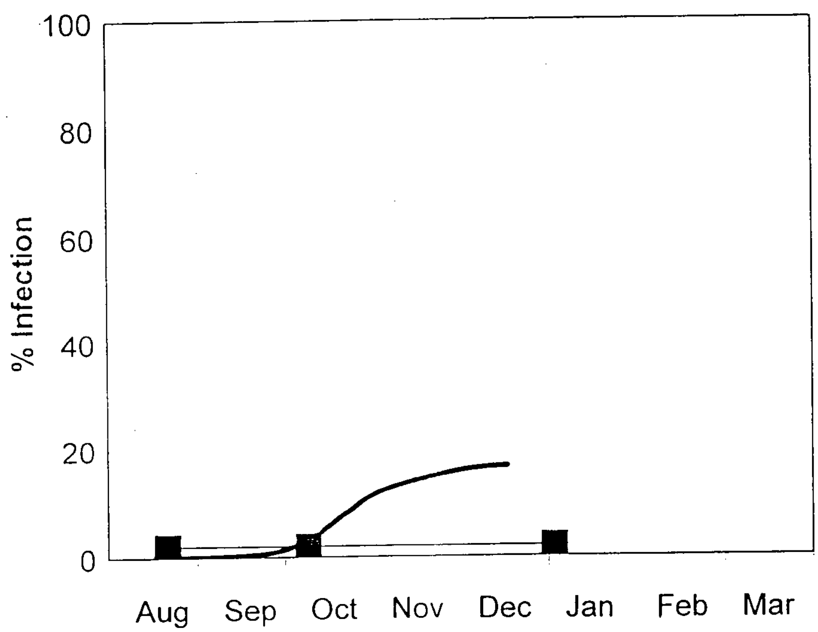


Figure 22b. Predicted vs observed BYDV incidence in barley, Auchincruive 1996/7.

Rothamsted 1997/8

Aphid numbers in unsprayed plots are shown in Fig 23. Numbers of bird cherry - oat aphid and grain aphid were much higher than in the previous season, and there were many more bird cherry - oat aphids (peak approximately 3000 per 12m wheat and 800 per 12m barley) than grain aphids (peak approximately 175 per 12m wheat and 225 per 12m barley). After a cold spell in mid October, numbers dropped, but the very warm conditions for the remainder of the year led to recovery of populations with no sustained fall until late December; much later than usual.

The model underestimated initial numbers of bird cherry – oat aphid in barley but was accurate for most of the season (Fig. 25a).

Virus incidence measured by visual inspection and by ELISA is shown in Fig 24. By both methodologies more virus is shown in wheat than in barley sprayed from the same date. More than twice as much virus is suggested by the visual inspection than by ELISA. Visual symptoms suggest an increase in spread throughout the season, but with a particularly noticeable increase in plots sprayed after19th November in barley and after 7th January in wheat. Unsprayed barley plots showed 89% infection and wheat plots 65%. ELISA tests suggest a dramatic increase in incidence between 19th December and 7th January in barley and between 7th January and 28th January in wheat. Unsprayed barley plots showed 34% infection and unsprayed wheat plots 15%. Using visual symptoms it was not possible to distinguish between the different virus isolates, but ELISA revealed the dominant isolate to be PAV. The presence of substantial MAV only in the control (unsprayed) plot is puzzling.

The model predicted initial and final virus incidence in barley accurately but peak infection was reached very much earlier in the model than in the field (Fig 25b).

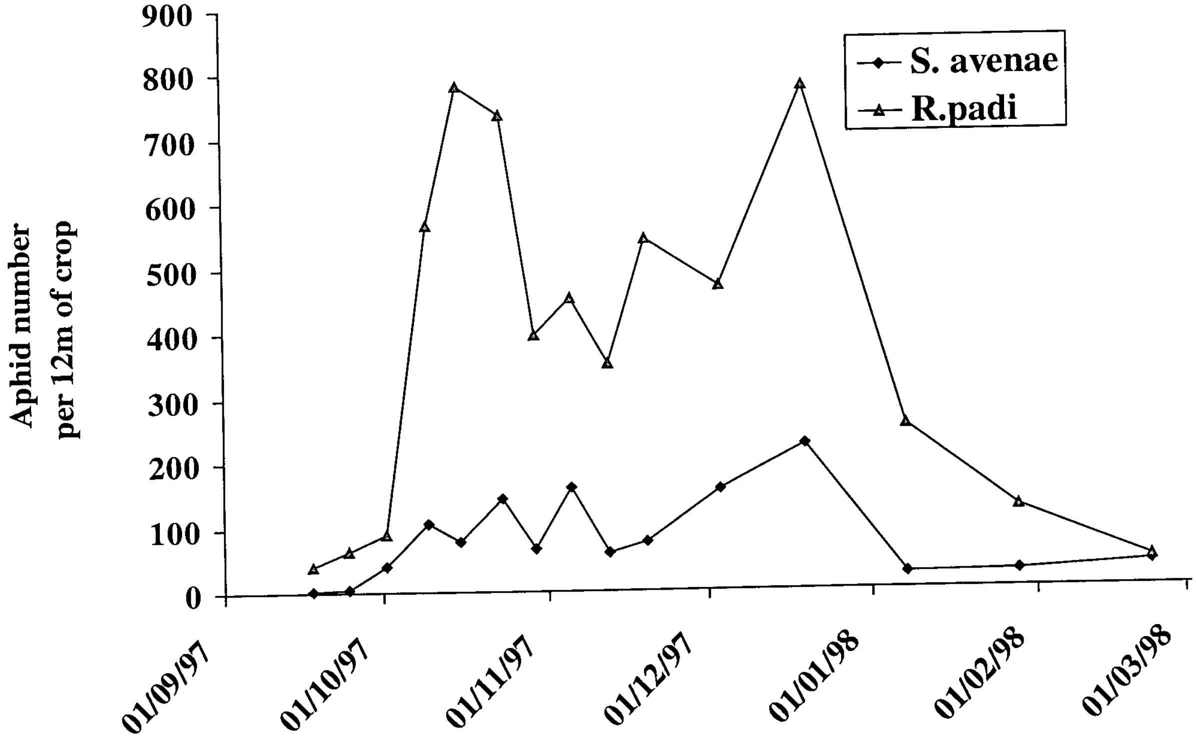


Figure 23a. Aphid numbers in unsprayed barley plots, Rothamsted 1997/8.

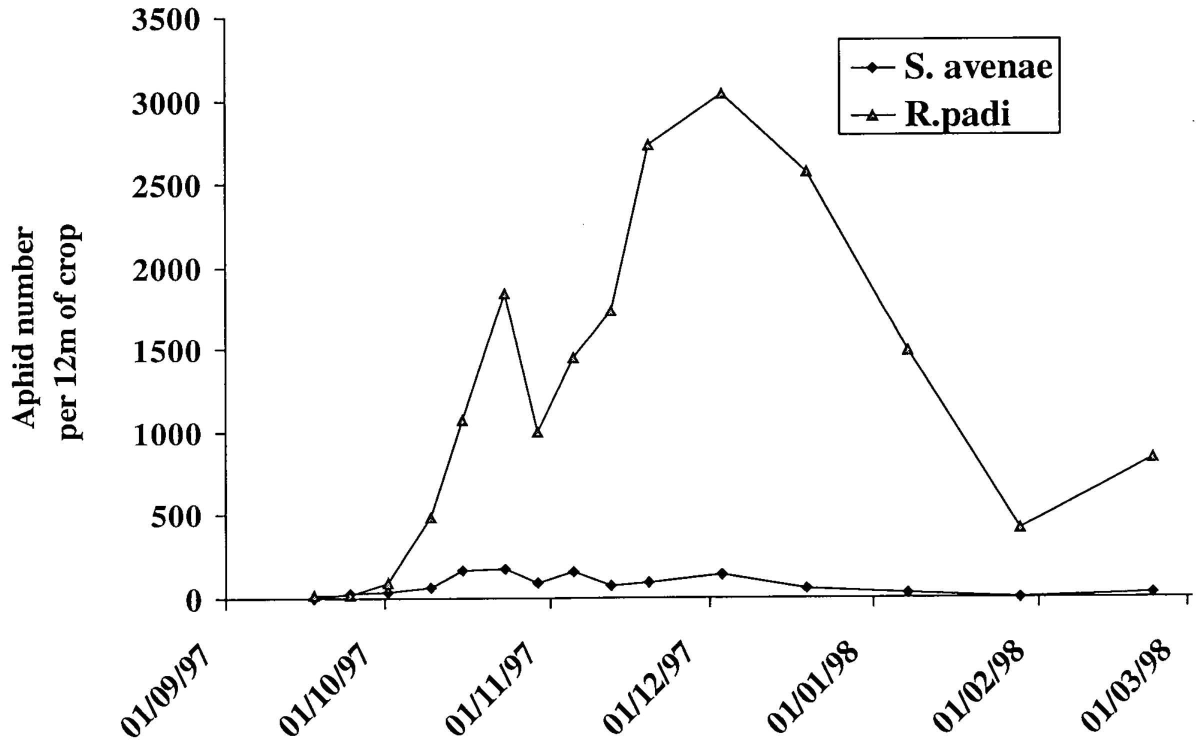


Figure 23b. Aphid numbers in unsprayed wheat plots, Rothamsted 1997/8.

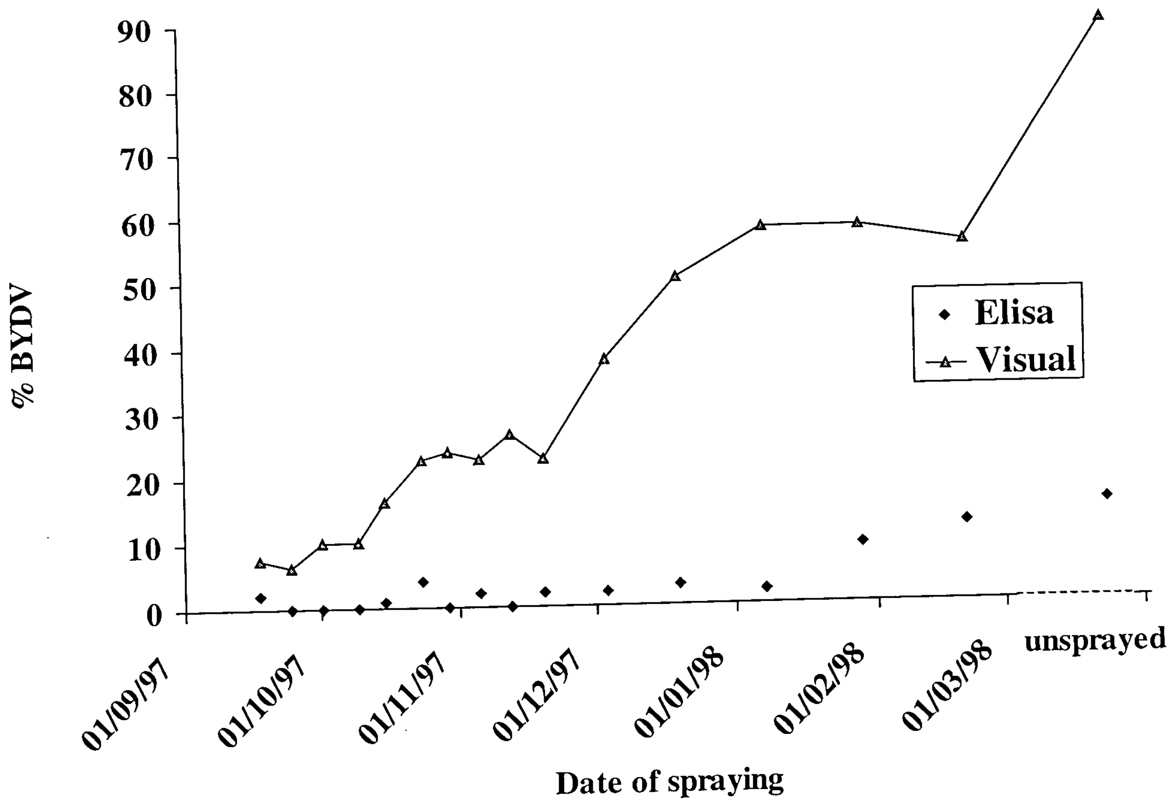


Figure 24a. BYDV incidence in barley plots, Rothamsted 1997/8.

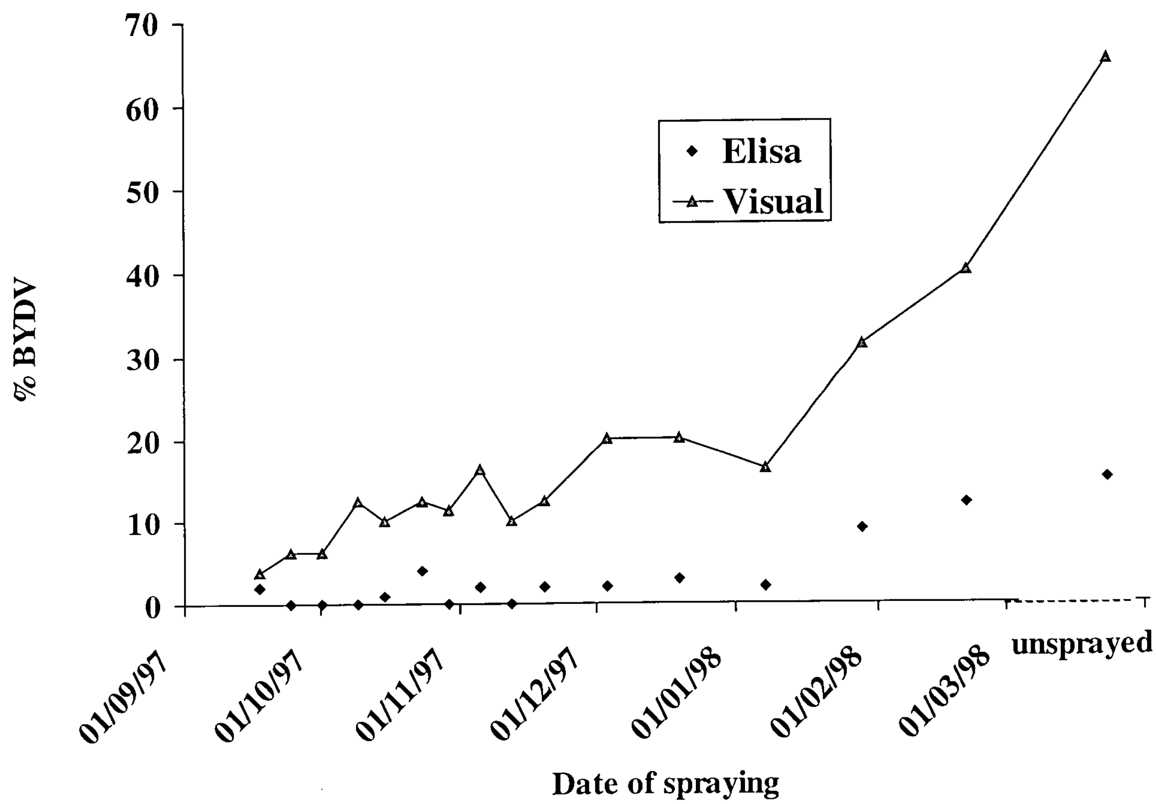


Figure 24b. BYDV incidence in wheat plots, Rothamsted 1997/8.

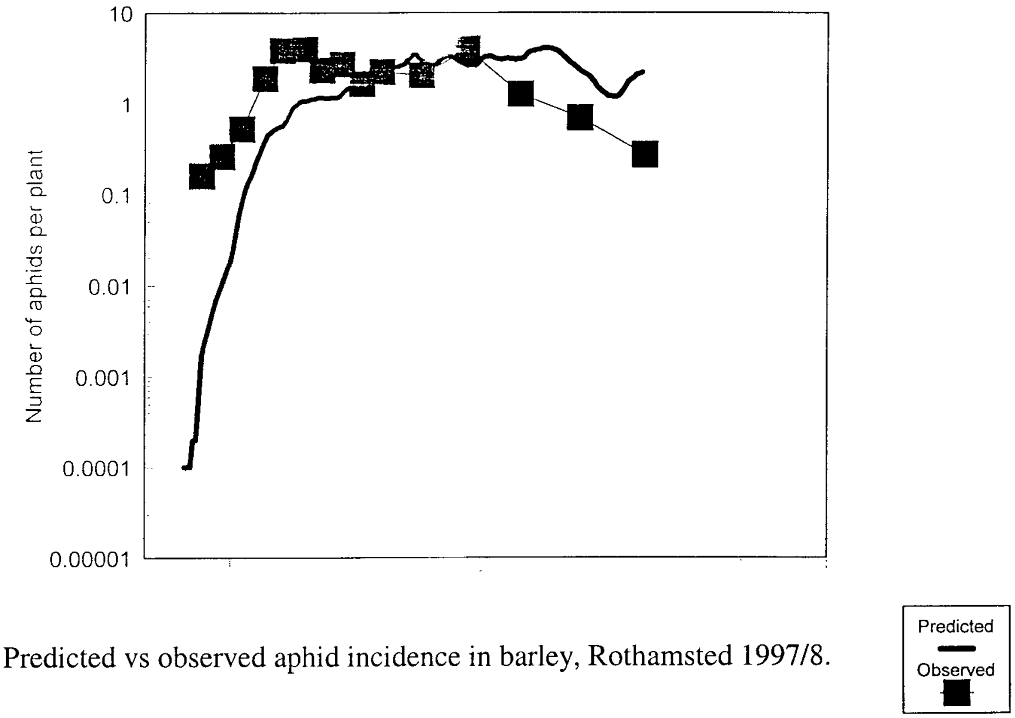


Figure 25a. Predicted vs observed aphid incidence in barley, Rothamsted 1997/8.

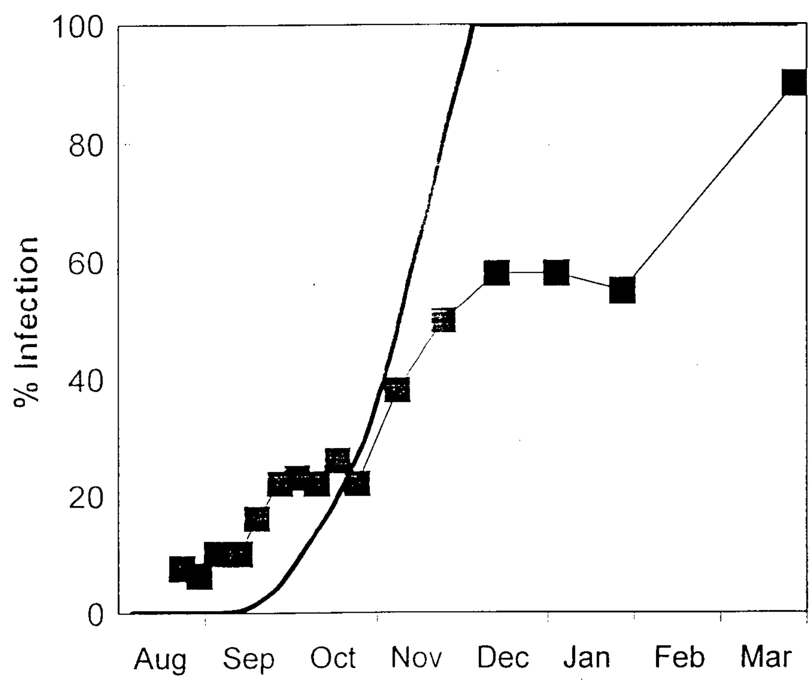


Figure 25b. Predicted vs observed BYDV incidence in barley, Rothamsted 1997/8.

Starcross 1997/8

Aphid numbers in unsprayed plots are shown in Fig 26. Numbers of aphids in barley were greater than in wheat and tailed off more rapidly in barley than in wheat. By mid December there were very few aphids in either crop.

The model underestimated initial numbers of bird cherry – oat aphid in barley but was accurate for most of the season (Fig. 28a).

Virus incidence measured by visual inspection and by ELISA is shown in Fig. 27. Visual symptoms peaked in barley (Fig. 27a) at 68% in crops sprayed on 2nd February and ELISA assessment at 34% in crops sprayed on 22nd December. Untreated crops had 65% infection according to visual assessment and 63% by ELISA assessment. In wheat (Fig. 27b) visual symptoms peaked at 63% in crops sprayed from 21st October and ELISA assessment at 45% in crops sprayed from 2nd February. Untreated crops had 78% infection according to visual assessment and 60% by ELISA assessment.

The model greatly overestimated virus incidence in barley sprayed from late November onwards (Fig. 28b).

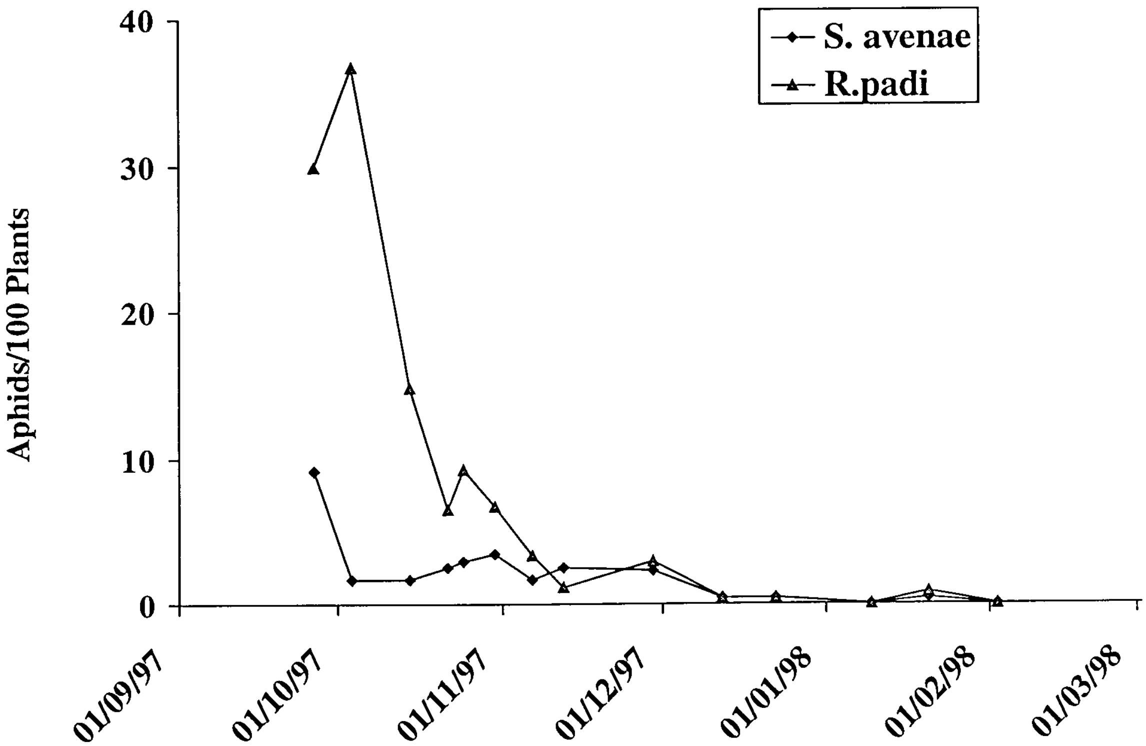


Figure 26a. Aphid numbers in unsprayed barley plots, Starcross 1997/8.

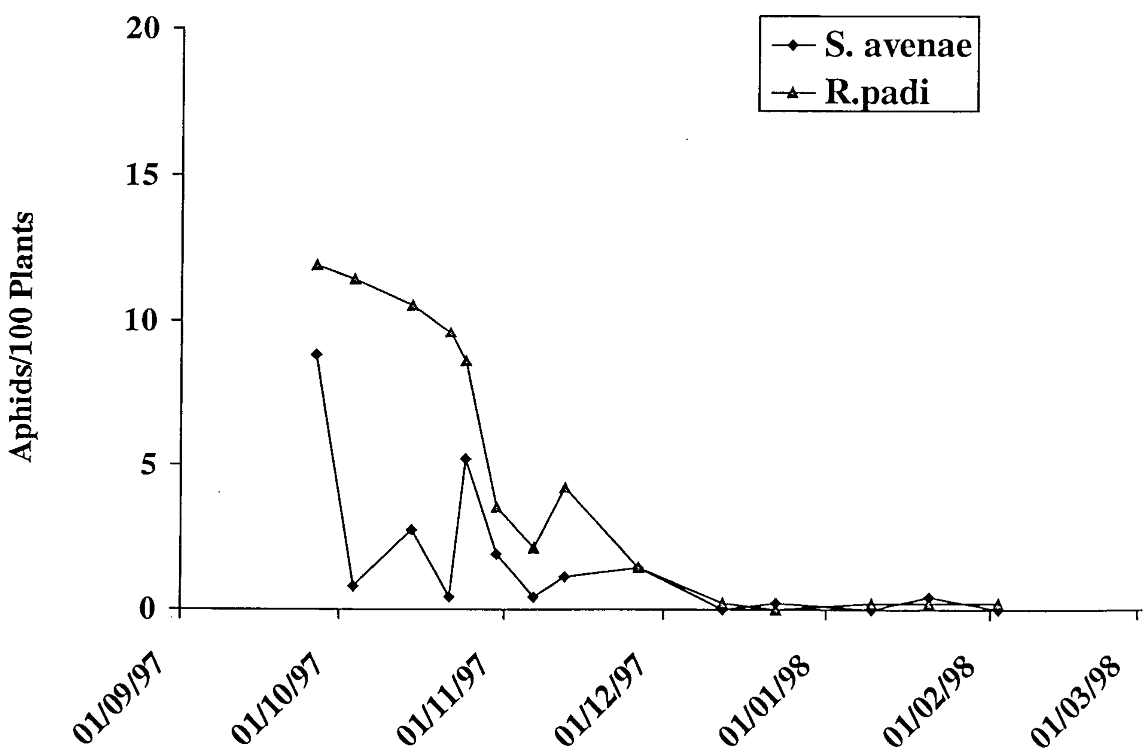


Figure 26b. Aphid numbers in unsprayed wheat plots, Starcross 1997/8.

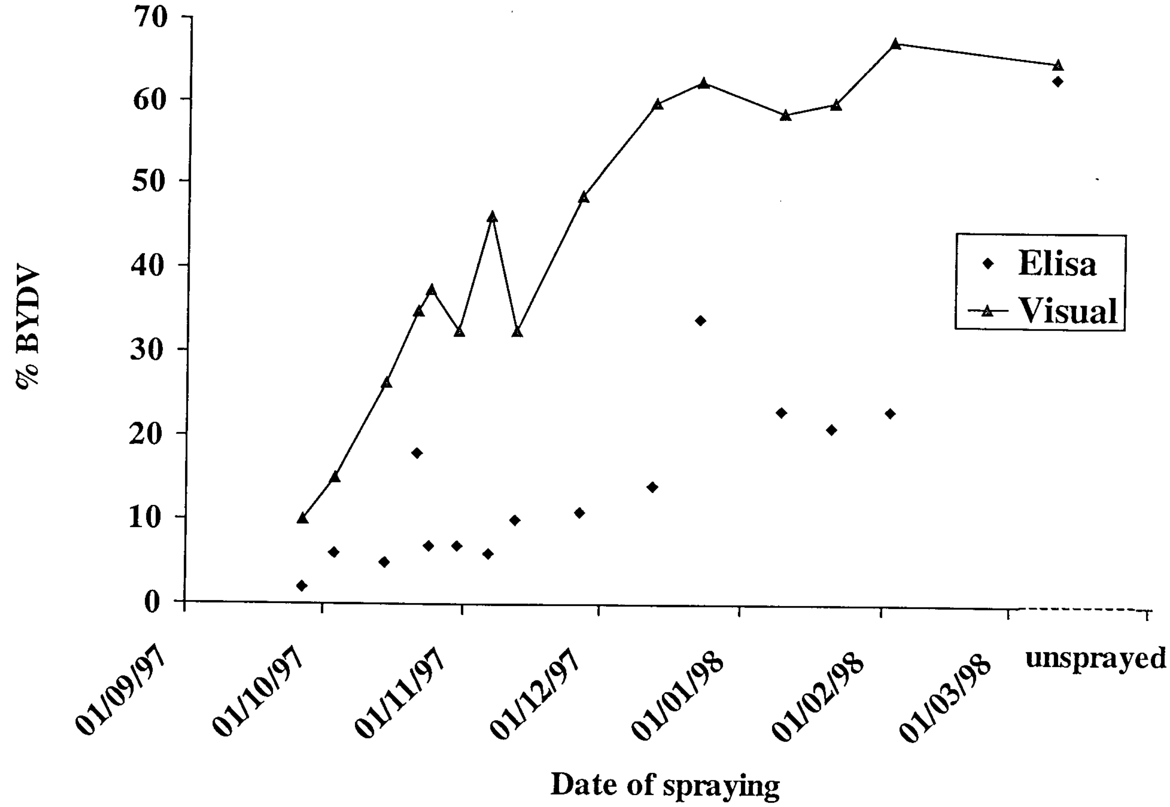


Figure 27a. BYDV incidence in barley plots, Starcross 1997/8.

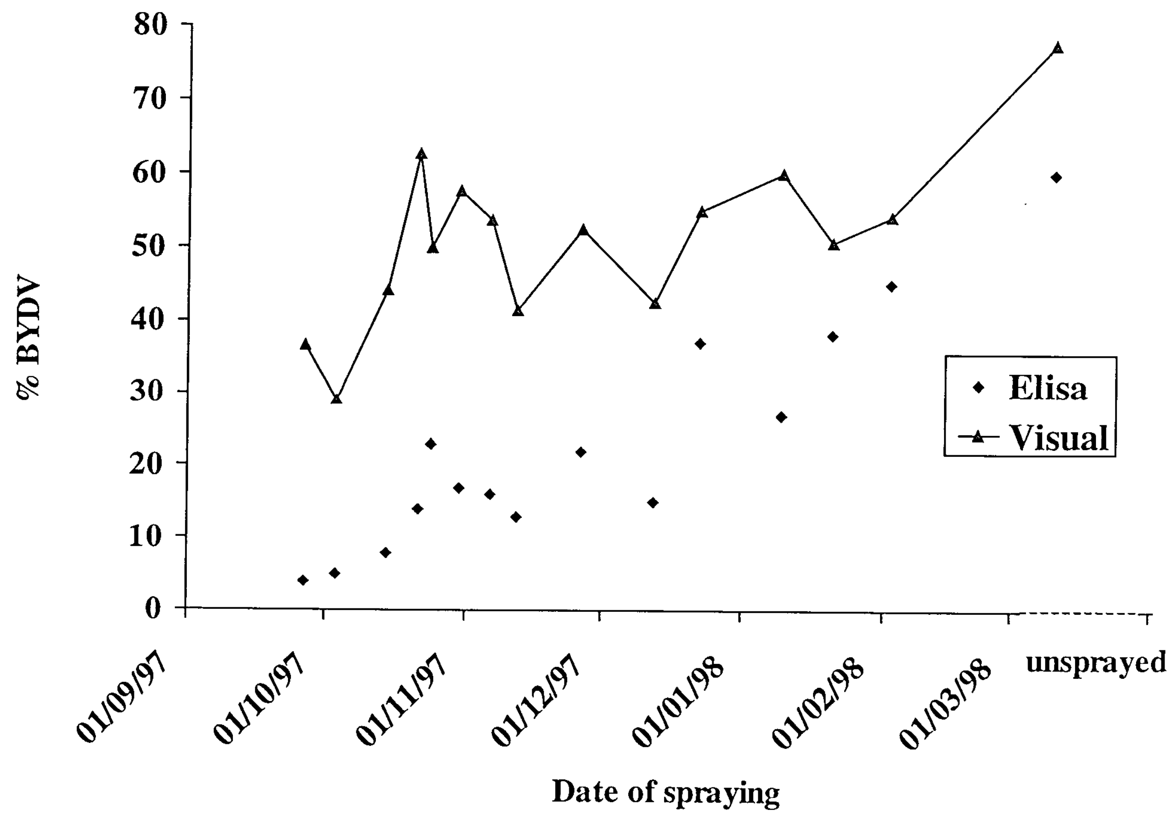


Figure 27b. BYDV incidence in wheat plots, Starcross 1997/8.

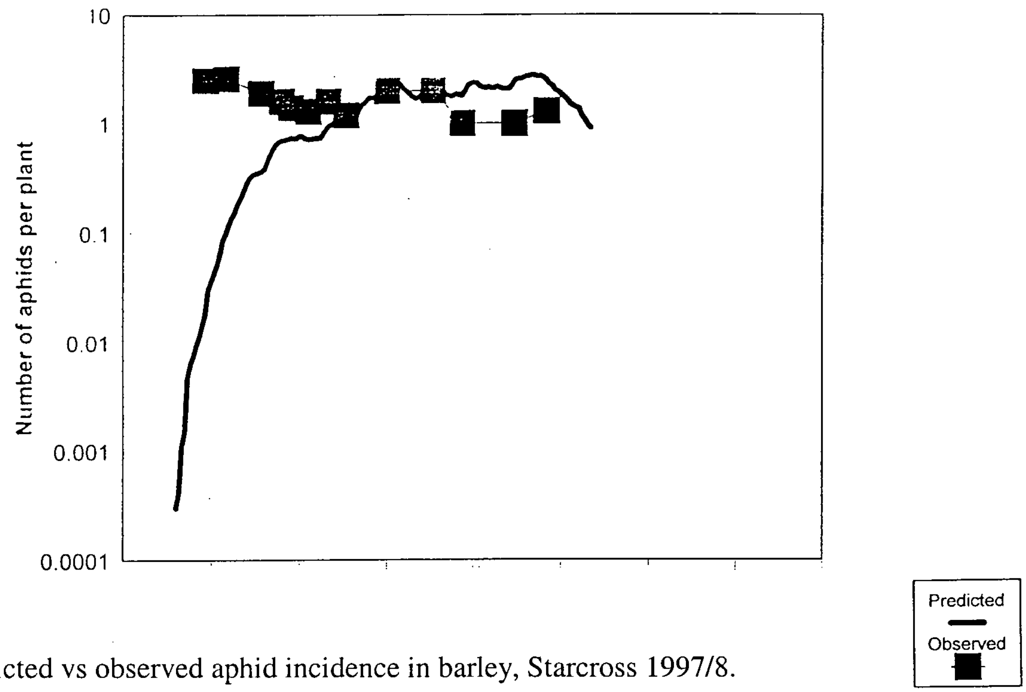


Figure 28a. Predicted vs observed aphid incidence in barley, Starcross 1997/8.

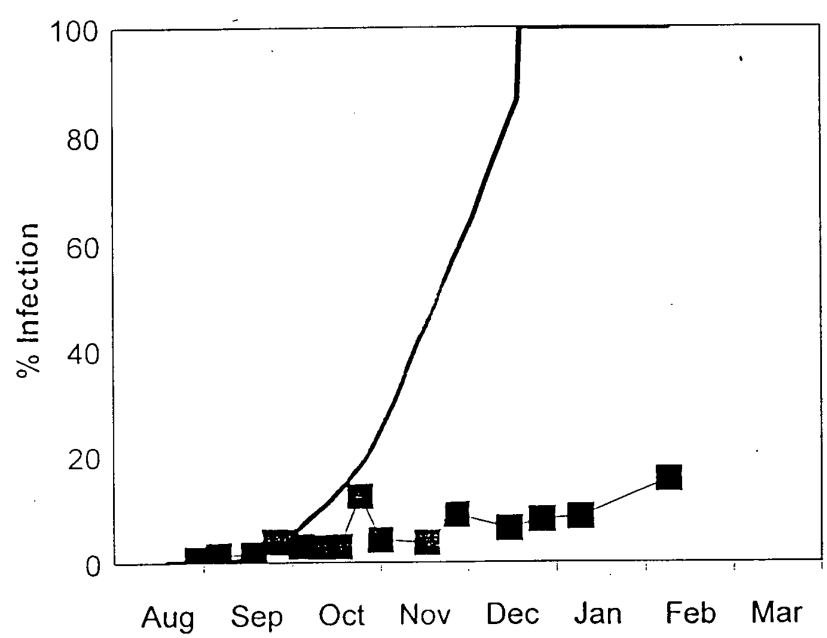


Figure 28b. Predicted vs observed BYDV incidence in barley, Starcross 1997/8.

Sensitivity analyses

Sensitivity analyses, whereby small changes were made to algorithms and the effects on predicted results compared, identified virus latent period within the plant host, aphid mortality, the number of infectious winged aphid immigrants and the dispersal rate of wingless aphids within a crop as critical factors which have a greater impact on model output than other factors.

Discussion

The variation in aphid numbers between sites and years was large, giving a good range of data against which to test the model. Only at Auchincruive in 1996/97 did actual aphid incidence bear no resemblance to model predictions. This may be due to limited data in the model on the effects of low temperature on aphid mortality, or to a much lower proportion of the bird cherry - oat aphid population being the cereal colonising form than in the south. The model predicted closely the early development of virus spread in all years and sites up to levels of virus that would have justified control. However, virus incidence later in the season was usually overestimated. This may be due to infected plants dying or becoming difficult to detect by ELISA over time so that the observed data are an underestimate of cumulative infections. There may also be some recently infected plants in which virus was not detected by ELISA.

The accuracy of the model predictions is encouraging and it would appear that the model could underpin a practical advisory tool. However, because of the complexity of the model it is impractical in its current format, and will therefore require further development and synthesis into a format suitable for use by decision-makers. It is intended that the forecasting model and subsequent DSS will generate weekly, field-specific estimates and forecasts of BYDV risk, with comprehensive interpretation, and recommendations for control in individual crops. Close interaction and collaboration with DESSAC developers has taken place throughout the project. All efforts have been made to ensure full DESSAC compliancy for the BYDV model, and the experience and knowledge gained from other MAFF-funded DESSAC-compliant DSS development (MAFF project No. AR0201) at CSL has been fully utilised in this project.

DISCUSSION

The epidemiology of BYDV is highly complex, involving numerous primary and lower order interactions between the abiotic environment and the crop, virus and vector components of the disease system (Burgess, Harrington & Plumb, 1999). In the sugar beet crop, long term and nationwide datasets have made it possible to examine statistical relationships between weather, aphid abundance and virus incidence. The relationships are used to forecast virus incidence and advise on the need for vector control. This approach has the advantage that it inherently takes into account all variables and interactions between them, but the disadvantage that it is not explanatory. In the case of BYDV, there are no sufficiently extensive virus datasets to allow a statistical approach to the problem. A mechanistic simulation approach based on experiment was therefore agreed as the best way forward. It will never be possible to do all the experiments necessary to parameterise such a model to provide a complete description of virus spread. Even if it was, the model could not form the basis for decision support as its complexity would severely limit its practicality. Thus, interactions considered likely to have the most effect on virus spread have been experimented upon and modelled and many assumptions made to fill gaps where data are unavailable. Even so, the run time of the model is still too great to provide sufficiently rapid responses to DESSAC enquiries, and simplification is required. This may involve, for example, removing the spatial element of the model, although the full spatial version would still be valuable as a research tool and would help to evaluate the reason behind any unsatisfactory performance of the model, and to highlight sensitive areas where further experimentation is desirable. Further algorithms may be added to the model whenever suitable data become available.

The regional nature of the model necessitated a statistical approach to allow its application to individual fields. This was achieved through an extensive survey of fields throughout the Country whereby aphid and virus incidence were correlated with a range of field characteristics. Where and when the regional risk of BYDV is considered very high, it may be necessary to spray all fields. Where and when the risk is very low, it may be possible to avoid spraying altogether. At other times the results of the survey will allow higher and lower risk fields to be identified and treated accordingly.

NEXT STEPS

1) The model needs to be simplified for the purpose of driving a decision support system. However, the full model must be maintained as an explanatory tool.

2) There are still questions concerning the initialisation of the model, particularly with respect to grain aphid. The use of trap plants to complement suction trap data warrants investigation.

3) Further data are required to quantify the effects of weather on aphid mortality in winter. Whilst data on this are already included, the model is particularly sensitive to this.

4) The model output is percentage of crop plants which are infected with BYDV. Ideally, data on yield effects of BYDV should be incorporated so that cost benefits from control can be estimated formally.

5) The model needs to be validated using data from commercial scale fields.

6) Models require maintenance. In order to run, the BYDV model will require routine data from suction traps on aphid incidence. As aspects of the biotic and abiotic environment change (eg winters become warmer, new crop varieties are introduced, new aphid species and/or virus isolates appear) new experimentation will be required in order to update model algorithms.

An extension to the complementary MAFF programme has been agreed and will tackle points 1 and 2.

CONCLUSION

This project has brought together, in the form of a mathematical model, all available data relevant to describing the epidemiology of BYDV in the UK. It has also produced the largest statistical comparison of field characteristics and BYDV incidence ever attempted. The model has been tested using independent data from small plots at three sites. For BYDV in barley, it has been very accurate at one site, reasonably accurate at another and poor at the third. Modification, simplification and commercial-scale evaluation are now required.

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