PROJECT REPORT No. 293

ASSESSING RESISTANCE OF UK WINTER WHEAT VARIETIES TO *SOIL-BORNE WHEAT MOSAIC VIRUS* AND *WHEAT SPINDLE STREAK MOSAIC VIRUS*

NOVEMBER 2002

Price £4.00

PROJECT REPORT No. 293

ASSESSING RESISTANCE OF UK WINTER WHEAT VARIETIES TO *SOIL-BORNE WHEAT MOSAIC VIRUS* AND *WHEAT SPINDLE STREAK MOSAIC VIRUS*

by

G BUDGE, C M HENRY

Central Science Laboratory, Sand Hutton, York, YO41 1LZ, UK

This the final report of a 36 month project, which started in September 1999. The work was funded by a grant of £56,341 from HGCA (project 2182).

CONTENTS

ABSTRACT

Soil-borne wheat mosaic virus (SBWMV) and *Wheat spindle streak mosaic virus* (WSSMV) cause serious diseases of winter wheat. Replicated field trials were set up in 5 fields in France and Italy over 3 seasons to assess the resistance of 23 varieties of UK winter wheat to infection by either SBWMV, WSSMV or a combination of both viruses.

The majority of the UK varieties tested became heavily infected with SBWMV showing typical symptoms, including leaf streaking and stunting. Few or no foliar symptoms were seen on varieties Aardvark, Charger, Claire, Cockpit, Hereward and XI19. Subsequent serological testing confirmed these varieties to be resistant or partially resistant to SBWMV. Of these, Claire, Charger, Hereward and XI19 are on the current 2002 recommended and provisionally recommended list and are therefore available for immediate use by UK farmers.

At a heavily infected site, the average yield of susceptible varieties was reduced by 42% when compared to the average yield of resistant varieties. The count of heads per m² at harvest was significantly reduced in susceptible varieties, suggesting SBWMV infection reduces tillering in UK varieties. At the most infected site, plant emergence was also reduced by SBWMV infection. None of the UK varieties became infected with WSSMV, which strongly indicates that these varieties are resistant to the virus.

SUMMARY

Soil-borne wheat mosaic virus (SBWMV) was first observed in the USA in 1919. The virus has since been reported in many countries including France and Italy. In France, SBWMV was first reported in 1978 and is now widely distributed in central and western regions. SBWMV is also found throughout much of Italy, in particular in the northern and central areas. The virus was detected in the UK for the first time in 1999 on a farm in Wiltshire. SBWMV has been found subsequently at two sites in Kent in 2000, and a further 3 sites in 2002 (Isle of Wight and again in Wiltshire and Kent).

Wheat spindle streak mosaic virus (WSSMV) is another soil-borne virus closely related to the barley mosaic viruses. In Europe, WSSMV was first detected in France in 1977, and is now known to occur throughout France and Italy. WSSMV is often found infecting wheat in combination with SBWMV, but this virus has not yet been reported in the UK.

The symptoms of both diseases include pale green or yellow mosaics on the leaves, stunting and reduced grain yield. In the UK the best visual symptoms occur from February to March and disappear as temperatures rise. Both viruses cause serious yield losses in susceptible varieties of winter wheat. Trials at the infected site in Wiltshire have shown that SBWMV can reduce grain yield in susceptible UK cultivars of winter wheat by up to 50%.

Both viruses are transmitted by the soil-borne plant parasite *Polymyxa graminis*, as are the soil-borne viruses of barley. The virus survives in resting spores of *P. graminis*, which can remain viable in the soil for decades. Once land is infected the only practical means of control is to grow resistant cultivars.

Replicated field trials were set up in 10 fields in France and Italy to assess the resistance of 23 varieties of UK winter wheat to infection by either SBWMV, WSSMV or a combination of both viruses. As the variety trials were started prior to the first UK outbreak of SBWMV, trial sites with a history of viral infection were chosen in France and Italy. Five infected fields were selected with either a single virus or a combination of both viruses.

2000

Ozzano, Italy (SBWMV)
Chambon sur Cisse, France (SBWMV and WSSMV)
Landes Le Gaulois, France (WSSMV)

2001

Minerbio, Italy (SBWMV)

Chambon sur Cisse, France (SBWMV and WSSMV).

2002

Ozzano, Italy (SBWMV)

Minerbio, Italy (SBWMV)

Rome, Italy (SBWMV and WSSMV)

Chambon sur Cisse, France (SBWMV and WSSMV)

Landes Le Gaulois, France (WSSMV)

Site management was carried out by the Institut Technique des Céréales et des Fourrages in France and the Università di Bologna in Italy. Resident farmers managed general crop husbandry according to local good farm practice. Plot size varied between countries (8m² in France and 10m² in Italy). Planting density was 400 seeds/m² in Italy and 250 seeds/m² in France and inter-row spacing was 17 cm for all sites.

Each season, 15 varieties of winter wheat were selected from the UK recommended and provisionally recommended lists to represent bread-making, cake/biscuit-making and feed wheats. Poor performing or obsolete varieties were substituted with new varieties in subsequent seasons. Variety list follows:

1999-2000	**2000-2001**	**2001-2002**
Aardvark	Aardvark	Aardvark
Consort	Consort	Consort
Charger	Charger	Charger
Shamrock	Shamrock	Shamrock
Malacca	Malacca	Malacca
Savannah	Savannah	Savannah
Napier	Napier	Napier
Claire	Claire	Claire
Hereward	Hereward	Hereward
Equinox	Equinox	Equinox
Riband	**Cockpit**	**XI19**
Reaper	**Eclipse**	**Biscay**
Buster	**Buchan**	**Deben**
Madrigal	Madrigal	**Option**
Rialto	Rialto	**Tanker**

Local varieties of known resistance to the viruses were incorporated into each field trial to act as controls. In France, these were Aztec (susceptible to SBWMV but resistant to WSSMV), Cezanne (susceptible to both viruses) and Tremie (resistant to both viruses). In Italy, the varieties Grazia and Valnova (both susceptible to both viruses) were used.

Symptom severity was assessed several times during the growing season using established disease indices (0-4 scale in Italy and a 0-5 scale in France where 0 = no visible symptoms and 4/5 = strong symptoms including foliar mottling and dwarfing). Assessments were grouped around times of maximum symptom expression.

The presence of each virus in plant material was confirmed using double antibody sandwich enzyme-linked immunosorbent assay (ELISA). Absorbance values greater than 3 times the mean negative control were considered to be positive.

Agronomic performance was evaluated in terms of grain yield (15% moisture in France and 13% moisture in Italy), thousand grain weight (TGW), heading date (Italian trials only) and plant height at harvest. In France, detailed plant emergence data and the number of heads per m^2 at harvest were recorded for each plot within the same 2 x $0.34m^2$ areas.

Symptom severity scores and ELISA results confirmed that susceptible local control varieties became infected with SBWMV at all sites. The most severe symptoms of SBWMV were evident in all 3 years at the site in Chambon sur Cisse. Strong foliar symptoms were accompanied by plant dwarfing and yield reductions in susceptible varieties. Varieties Aardvark, Charger, Claire, Cockpit, Hereward and XI19 showed little or no foliar symptoms on SBWMV-infected land at any of the sites. ELISA confirmed the absence of SBWMV in the majority of leaves for all of these varieties except Aardvark, where the virus was consistently found at low levels.

At Chambon sur Cisse the average yields of resistant and susceptible varieties were respectively 8.21 and 4.76 t/ha in 2000, representing a 42% reduction in yield. The corresponding yield reductions in 2001 and 2002 respectively were 32% and 33%

At the Italian sites, UK varieties were not challenged sufficiently with the virus to cause severe yield loss. However, symptomatology and ELISA data showed the same trend as the results obtained at the sites in France, showing that the cultivars Charger, Claire, Cockpit, Hereward and XI19 were consistently resistant to SBWMV infection. Whilst virus particles were detected in the leaves of Aardvark, little or no reduction in yield was recorded suggesting this variety is partially resistant.

The majority of UK winter wheat varieties tested during the study were susceptible to infection by SBWMV in France and Italy. At heavily infected sites, e.g. Chambon sur Cisse in 2000, virus infection significantly reduced the average yield for susceptible varieties by 42% when compared to the average yield for resistant varieties. Furthermore, since the plants were not infected with WSSMV, this yield loss can be attributed to SBWMV infection alone. This large yield reduction was caused by a significant reduction in the number of heads per m^2. For example, at Chambon sur Cisse, yield was consistently positively correlated with the number of heads per m^2 and negatively correlated to symptom severity in both seasons. These results suggest that SBWMV reduces tillering in UK varieties of winter wheat.

The origin of resistance to SBWMV is unknown, although the variety Moulin has been implicated as a possible resistance source. The mechanisms for resistance are also unclear, however, the lack of virus in leaf material of resistant varieties suggests resistance may act by reducing virus movement to the aerial parts. The large variation in virus infection between sites, even between the same site in different years, highlights the importance of environmental conditions in determining whether severe disease will occur. Basic analysis of meterological data collected at the Chambon sur Cisse site over the three years suggests heavy rainfall coupled with average daily temperatures of 10-15°C within 2-3 weeks post-planting may increase disease severity.

Symptom severity and ELISA of leaf material from the susceptible control variety (Cezanne) at 5 out of 6 WSSMV infected sites revealed heavy infection with WSSMV. However, no definite symptoms of WSSMV were observed on any UK varieties at any infected site, despite strong symptoms in susceptible control varieties. WSSMV failed to develop at the trial site in Chambon sur Cisse in 2000, where Cezanne remained healthy.

All 23 UK varieties tested were apparently resistant to WSSMV. The virus was not detected in the leaves or roots of any of the varieties. It has previously been observed that a mixed infection of SBWMV and WSSMV can enhance viral infection and break down varietal resistance to SBWMV but this was not found to be the case in these trials.

The 2001-2002 trial was duplicated, in association with ADAS and funded by DEFRA, on an infected site in Wiltshire, UK. The results indicate even greater yield reductions than found within this project. In Wiltshire, SBWMV infection reduced the average yield for susceptible varieties by over 50% when compared to the average yield for resistant varieties.

TECHNICAL DETAIL

INTRODUCTION

Soil borne wheat mosaic virus (SBWMV), the type member of the genus *Furovirus*, was first observed in Illinois and Indiana in 1919 but has spread to at least 16 states and probably occurs throughout the winter wheat growing area of the USA (Brakke & Langenberg, 1988). The virus has since been reported from Canada, South America (Brazil), Asia (China, Japan), Africa (Zambia) and Europe (Denmark, France, Germany, Italy, Poland) (Brakke, 1971; Canova and Quaglia, 1960; Hariri *et al*., 1987). In France, SBWMV was first reported in 1978 and is now widely distributed in central and western regions. SBWMV is also found throughout much of Italy, in particular in the northern and central areas. The virus was detected in the UK for the first time in 1999 on a farm in Wiltshire (Clover *et al*., 2001). SBWMV has been found subsequently at two sites in Kent in 2000, and in 2002 on the Isle of Wight and one further site in Wiltshire.

Wheat spindle streak mosaic virus (WSSMV) is another soil-borne virus closely related to the barley mosaic viruses, *Barley yellow mosaic virus* and *Barley mild mosaic virus*. In Europe, WSSMV was first detected in France in 1977 (Signoret *et al.*, 1977), and is now known to occur throughout France, Germany and Italy. WSSMV is often found infecting wheat in combination with SBWMV, but this virus has not yet been reported in the UK.

The symptoms of both diseases depend on the virus strain and host cultivar and include pale green or yellow mosaics on the leaves, stunting, reduced tillering and grain yield. Symptom severity and virus titre is dependent on temperature and can fluctuate during the season. The best visual symptoms generally occur in the spring (February to April in Europe) and disappear as temperatures rise. Both viruses cause serious yield losses in susceptible varieties of winter wheat. Losses of up to 56% have been recorded in cases of mixed infection in durum wheat (V. Vallega, pers. com.). Trials at the infected site in Wiltshire have shown that SBWMV can reduce grain yield in susceptible UK cultivars of winter wheat by up to 50% (Clover *et al*., 2001).

Both viruses are transmitted by the soil-borne plant parasite *Polymyxa graminis* Led., as are the soil-borne viruses of barley. The virus survives in the absence of host plants in the resting spores of *P. graminis*, which can remain viable in the soil for at least 15 years. Experience of the spread of SBWMV in other countries, together with the spread of barley mosaic viruses in the UK, indicate that there is a high risk of SBWMV and WSSMV becoming widespread in the UK. Once land is infected the only practicable means of control is to grow resistant cultivars. In France, cultivars with virus resistance have been identified (e.g. Cadenza and Tremie) and breeding work is in progress to produce improved cultivars for the future. Prior to this study, little was known about virus resistance in UK varieties of winter wheat. The work presented here is the first resistance data for UK cultivars of winter wheat comparing symptomatology, virus infection and final yield data.

MATERIALS AND METHODS

Crop and site details

As the variety trials were started prior to the first UK outbreak of SBWMV, trial sites with a history of viral infection were chosen in France and Italy. Ten variety trials were completed from 1999-2002 in 5 fields infected with either a single virus or a combination of both viruses. During the 1999-2000 season: Ozzano, Italy (SBWMV); Chambon sur Cisse, France (SBWMV and WSSMV); and Landes Le Gaulois, France (WSSMV). During the 2000-2001 season: Minerbio, Italy (SBWMV); and Chambon sur Cisse, France (SBWMV and WSSMV). During the 2001-2002 season: Ozzano, Italy (SBWMV); Minerbio, Italy (SBWMV); Rome, Italy (SBWMV and WSSMV); Chambon sur Cisse, France (SBWMV and WSSMV); and Landes Le Gaulois, France (WSSMV). Site management was carried out by the Institut Technique des Céréales et des Fourrages in France; the Università di Bologna in Minerbio and Ozzano; and the Istituto Sperimentale per la Cerealicoltura in Rome. Resident farmers managed general crop husbandry according to local good farm practice.

Variety list

Fifteen winter wheat varieties (Aardvark, Buster, Charger, Claire, Consort, Equinox, Hereward, Madrigal, Malacca, Napier, Reaper, Rialto, Riband, Savannah and Shamrock) were selected from the UK recommended and provisionally recommended national lists to represent bread-making, cake/biscuit-making and feed wheats. Poor performing or obsolete varieties (Buster, Reaper and Riband in 2001 and Cockpit, Eclipse and Buchan in 2002) were substituted with new varieties (Buchan, Cockpit and Eclipse in 2001 and XI19, Biscay and Deben in 2002) in subsequent seasons.

Local varieties of known resistance to the viruses were incorporated into each field trial to act as controls. In France, these were Aztec (susceptible to SBWMV but resistant to WSSMV), Cezanne (susceptible to both viruses) and Tremie (resistant to both viruses). In Italy, the varieties Grazia and Valnova (both susceptible to both viruses) were used.

Experimental design and statistical analysis

A randomised block design with 3 or 4 replicates of each variety was used for all 5 trials. Plot size varied between countries ($8m^2$ in France and $10m^2$ in Italy). Planting density was 400 seeds/m^2 in Italy and 250 seeds/m^2 in France and inter-row spacing was 17 cm for all sites. All data were analysed using ANOVA. Friedman's test was used for analysis of symptom severity scores because these data were discontinuous (df 14). Data were correlated as required using Pearson's or Spearman rank correlation as appropriate. Data for local control varieties were removed for all statistical tests.

Assessments

Symptom severity was assessed several times during the growing season using established disease indices (0-4 scale in Italy and a 0-5 scale in France where 0 = no visible symptoms and 4/5 = strong symptoms including foliar mottling and dwarfing). Assessments were grouped around times of maximum symptom expression. Data from the assessments showing highest foliar disease levels are presented.

The presence of each virus was confirmed using double antibody sandwich enzyme-linked immunosorbent assay (ELISA) essentially as described by Vallega *et al.* (1999). Absorbance values greater than 3 times the mean negative control were considered to be positive. Sampling varied slightly between sites; in France leaves were collected from 10 random plants from each plot and pooled by variety. A sub-sample of 5 leaves was then tested by ELISA. Whole plants were sampled from the site in Chambon sur Cisse in 2000 as described and roots also tested. In Italy, the second youngest leaf was sampled from 10 random plants from each plot. These were pooled and tested using ELISA.

Agronomic performance was evaluated in terms of grain yield (15% moisture in France and 13% moisture in Italy), thousand grain weight (TGW), heading date (Italian trials only) and plant height at harvest. In France, detailed plant emergence data and the number of heads per m^2 at harvest were recorded for each plot within the same 2 x $0.34m^2$ areas.

RESULTS

SBWMV

Symptom severity scores and ELISA results confirmed that susceptible local control varieties became infected with SBWMV at all sites. The most severe symptoms of SBWMV were evident in all three years at the site in Chambon sur Cisse. Strong foliar symptoms were accompanied by plant dwarfing and yield reductions in susceptible varieties (Table 1-3). Varieties Aardvark, Charger, Claire, Cockpit, Hereward and XI19 showed little or no foliar symptoms on SBWMV-infected land at any of the sites. ELISA confirmed the absence of SBWMV in the leaves of all of these varieties except Aardvark, where the virus was consistently found at low levels. At Chambon sur Cisse the average yields of resistant and susceptible varieties were respectively 8.21 and 4.76 t/ha in 2000, representing a 42% reduction in yield. The corresponding yield reductions in 2001 and 2002 respectively were 32% and 33%.

SBWMV infection at the sites in Ozzano in 2000 and Rome in 2002 was mild with infection starting very late in the season. No variety was consistently infected with the virus (Table 6, 10). In Rome in 2002, poor soil conditions at planting produced uneven emergence and caused some seed to be dragged into neighbouring plots. Severely affected plots were removed from the analysis. Yields for the remaining plots were adjusted to compensate for actual plot area planted. Severe, patchy infection at the site in Ozzano in 2002, reduced plant density and prevented the collection of any post harvest data. Despite good infection and symptom expression in control varieties, SBWMV failed to develop consistently in the UK varieties for both years at the site in Minerbio (Table 8, 9). Grain yield for the UK varieties grown on all Italian sites was not badly affected by this low level of virus infection (Table 6-10). Reductions in yield between resistant and susceptible varieties varied from 18% at the site in Minerbio in 2001 to 4% at the site in Ozzano in 2001. Symptomatology and ELISA results showed similar trends to the results from the French trials. Varieties Aardvark, Charger, Claire, Cockpit, Hereward and XI19 showed little or no foliar symptoms.

Yield positively correlated with number of heads per m^2, but negatively correlated with symptom severity, for all years at the Chambon sur Cisse site. Also, plant height at harvest and showed a significant negative relationship with symptom severity (Table 11-13). Significant differences were observed between varieties for TGW at all sites, including Landes Le Gaulois, irrespective of viral infection. Disease severity negatively correlated with plant emergence at Chambon sur Cisse in 2000.

WSSMV

Symptom severity and ELISA of leaf material from the susceptible control variety (Cezanne) at 5 out of 6 WSSMV infected sites revealed heavy infection with WSSMV (Table 2-5, 11). However, no definite symptoms of WSSMV were observed on any UK varieties at any infected site, despite strong symptoms in susceptible control varieties. WSSMV failed to develop at the trial site in Chambon sur Cisse in 2000, where Cezanne remained healthy (Table 1).

DISCUSSION

The majority of UK winter wheat varieties tested during the study were susceptible to infection by SBWMV in France and Italy. At the most heavily infected site, virus infection significantly reduced the average yield for susceptible varieties by 42% when compared to the average yield for resistant varieties. Furthermore, since the plants were not infected with WSSMV, this yield loss can be attributed to SBWMV infection alone. This large yield reduction was caused by a significant reduction in the number of heads per m^2. For example, in all 3 seasons at Chambon sur Cisse, yield was positively correlated with the number of heads per m^2 and negatively correlated to symptom severity. These results suggest that SBWMV reduces tillering in UK varieties of winter wheat and. Previous studies have implicated a reduction in tillering as the main cause of yield loss in SBWMV-infected wheat (Kucharek and Walker, 1974; Campbell *et al.*, 1975). At the site in Chambon sur Cisse in 2000, symptom severity negatively correlated with plant emergence (Table 11). This suggests early, severe infection by SBWMV may reduce plant emergence by increasing seedling mortality sometime within the first 4 weeks.

At the sites in Italy, UK varieties were not challenged sufficiently with the virus to cause large yield reductions. However, symptomatology and ELISA data showed the same trend as the results obtained at the sites in France, showing that the cultivars Charger, Claire, Cockpit, Hereward and XI19, were consistently resistant to SBWMV infection. Whilst virus particles were detected in the leaves of Aardvark, little or no reduction in yield was recorded, suggesting this variety is partially resistant.

Of the varieties identified as resistant, Claire, Charger, Hereward and XI19 are on the current 2002 recommended and provisionally recommended list and are therefore available for immediate use by UK farmers. However, resistant varieties of winter wheat have appeared on the recommended list by chance. UK breeders do not actively select for SBWMV resistance. In order to secure the future of growing winter wheat on infected land in the UK, resistance to SBMWV should be incorporated into the current breeding strategy.

The origin of resistance to SBWMV is unknown, although the variety Moulin has been implicated as a possible resistance source. The mechanisms for resistance are also unclear, however, the lack of virus in leaf material of resistant varieties suggests resistance may act by reducing virus movement to the aerial parts. Driskel *et al.* (2002) recently concluded that virus resistance in hard red winter wheat probably operates in the roots to block virus movement to the leaves. Clearly there is a need to research resistance mechanisms more thoroughly in the future.

The large variation in virus infection between sites, even between the same site in different years, highlights the importance of the environment in determining whether severe disease will occur. Also, the possibility of a reduction in plant emergence due to high disease pressure, suggests the importance of weather immediately post-planting. Basic analysis of meterological data collected at the Chambon sur Cisse site over the three years showed short periods of heavy rainfall coupled with average daily temperatures of 10-15°C within 2-3 weeks post-planting may have encouraged infection (data source Météo-France/ITCF). Successive periods of wet and dry are known to favour the lifecycle of *P.graminis* (Adams *et al.*, 1986) and the optimum temperature for *P. graminis* infection is thought to be between 10-15°C.

All 18 UK varieties tested are resistant to WSSMV. The virus was not detected in the leaves or roots of any of the varieties. It has previously been observed that a mixed infection of SBWMV and WSSMV can enhance viral infection and break down varietal resistance to SBWMV (Brakke & Langenberg, 1988) but this was not found to be the case in these trials.

Recent work has duplicated the 2002 trial at an infected site in Wiltshire to investigate whether similar yield reductions can be recorded in the UK climate, and to help validate the findings of this project. Worryingly, the results indicate even greater yield reductions than found at Chambon sur Cisse in 2000. In Wiltshire, SBWMV infection reduced the average yield for susceptible varieties by over 50% when compared to the average yield for resistant varieties.

ACKNOWLEDGEMENTS

We would like to thank C. Ratti and C Rubies-Autonell at the Università di Bologna, M Bonnefoy at the Institut Technique des Céréales et des Fourrages and V. Vallega at the Istituto Sperimentale per la Cerealicoltura for completing the field work.

REFERENCES

Adams MJ; Swaby AG; Macfalane I (1986). The susceptibility of barley cultivars to barley yellow mosaic virus (BaYMV) and its fungal vector *Polymyxa graminis*. *Annals of Applied Biology* **109**, 561-72.

Brakke MK (1971). Soil-borne wheat mosaic virus. CMI/AAB Descriptions of Plant Viruses, no. 77. Wallingford, UK: CAB International.

Brakke M K; Langenberg W G (1988). Experiences with soil-borne wheat mosaic virus in North America and elsewhere. In: *Developments in Applied Biology II. Viruses with Vectors,* eds J I Cooper & M J C Asher, pp. 183-202. Association of Applied Biologists: Wellesbourne, UK.

Campbell L G; Heyne E G; Gronau D M; Niblett C (1975). Effect of *Soil-borne wheat mosaic virus* on wheat yield. *Plant Disease Reporter* **59**, 472-476.

Canova A; Quaglia A (1960). Il mosaico del frumento. *Informatore fitopatologico* **10**, 206-208

Clover G R G; Wright D; Henry C M (2001). Occurrence of *Soil-borne wheat mosaic virus* in the UK. In: *Proceedings of the Fourth Symposium of the International Working Group on Plant Viruses with Fungal Vectors, 1999*, eds J L Sherwood & C M Rush, pp.105-108. American Society of Sugar Beet Technologists: Denver, USA.

Driskel B A; Hunger R M; Payton M E; Verchot-Lubicz J (2002). Response of hard red winter wheat to *Soil-borne wheat mosaic virus* using novel inoculation methods. *Phytopathology* **92**, 347-354.

Hariri D; Courtillot M; Zaoui P; Lapierre H (1987). Multiplication of *Soil-borne wheat mosaic virus* (SBWMV) in wheat roots infected by a soil carrying SBWMV and *Wheat yellow mosaic virus* (WYMV). *Agronomie* **7**, 789-796.

Kucharek T A; Walker J A (1974). The presence of and damage caused by Soil-borne wheat mosaic virus in Florida. *Plant Disease Reporter* **58**, 763-765.

Signoret P A; Alliot B; Poinso B (1977). Présence en France du Wheat spindle streak mosaic virus. *Annales de Phytopathologie* **9**, 377-379.

Vallega V; Rubies-Autonell C; Turina M; Ratti C; Contoli S (1999). Reactions of durum wheat cultivars to infections by SBWMV grown in northern Italy during 1995-96 *Journal of Plant Diseases and Protection* **106**, 284-290.

APPENDIX A

Table 1 Chambon sur Cisse 2000 (SBWMV+WSSMV)

Variety	Symptom severity (0-5) 09/03/00	Symptom severity (0-5) 03/05/00	Leaves positive (of 5) ELISA 27/03/00 SBWMV	WSSMV	Yield (t/ha) at 15% Humidity	Height (cm)	Emergence (plants/m²) 17/11/99	Number of heads/m² 12/07/00
Aztec	3.3	5.0	5	0	4.64	49.6	281.0	375.0
Cezanne	5.0	5.0	4	0	3.46	48.3	265.0	255.9
Tremie	0.0	0.0	0	0	8.23	80.0	262.3	411.3
Aardvark	0.0	1.7	1	0	7.43de	77.0de	301.3	397.5bcde
Charger	0.0	0.0	0	0	8.88e	75.6cde	259.7	470.6de
Claire	0.0	0.0	0	0	8.34e	79.7e	254.0	421.6cde
Hereward	0.0	0.0	0	0	8.19e	80.3e	274.0	483.3e
Buster	4.7	5.0	4	0	5.38bc	53.4ab	239.3	344.1abcd
Consort	5.0	5.0	4	0	4.83bc	51.3ab	257.3	292.2ab
Equinox	5.0	5.0	5	0	2.24a	49.7ab	251.3	231.4a
Madrigal	4.7	5.0	5	0	4.28b	49.0a	251.3	368.1bcde
Malacca	3.7	5.0	5	0	5.82cd	51.8ab	250.7	382.8bcde
Napier	4.7	5.0	3	0	4.95bc	51.6ab	238.3	353.4abcde
Reaper	4.3	4.3	5	0	4.71bc	57.6abcd	238.7	312.3abc
Rialto	4.3	3.7	5	0	4.93bc	65.5bc	277.3	310.3abc
Riband	4.7	5.0	4	0	4.54bc	55.0ab	243.0	281.4ab
Savannah	5.0	5.0	5	0	5.33bc	56.4abc	242.0	274.5ab
Shamrock	4.3	5.0	4	0	5.35bc	48.3a	232.0	380.4bcde
P-Value (28 df)	0.001	<0.001	-	-	<0.001	<0.001	0.09	<0.001
SED	-	-	-	-	0.472	4.99	19.17	39.67

Table 2 Chambon sur Cisse 2001 (SBWMV+WSSMV)

Variety	Symptom severity (0-5) 29/03/01	Symptom severity (0-5) 22/05/01	Results for SBWMV ELISA 24/04/01 (average of 5 plants) Leaves	Roots	Results for WSSMV ELISA 24/04/01 Leaves	Yield (t/ha) at 15% humidity	Height (cm)	Emergence (plants/m²) 29/11/00	Number of heads/m² 27/06/01
Aztec	4.3	5.0	+	+	-	3.35	50.9	227.0	243.1
Cezanne	4.3	5.0	+	+	+	2.72	41.8	190.7	147.1
Tremie	0.0	0.0	-	+	-	5.96	78.3	198.0	245.6
Aardvark	0.3	0.0	-	+	-	5.14defg	65.0de	212.3	239.2
Charger	0.0	0.0	-	+	-	5.77fg	70.0ef	205.9	325.0
Claire	0.0	0.0	-	+	-	5.88fg	70.0ef	205.4	267.2
Cockpit	1.3	0.0	-	+	-	6.02g	80.0f	243.1	273.0
Hereward	0.0	0.0	-	+	-	5.59efg	70.0ef	231.4	278.0
Buchan	5.0	5.0	+	+	-	2.86a	40.2a	174.0	160.8
Consort	4.0	4.0	+	+	-	3.52abc	54.7cd	167.7	190.7
Eclipse	4.0	3.7	+	+	-	3.86abcd	45.7abc	193.6	199.0
Equinox	3.7	3.0	+	+	-	3.48ab	51.8abc	228.9	209.8
Madrigal	4.7	5.0	+	+	-	3.67abc	43.9abc	180.9	157.8
Malacca	3.0	3.3	+	+	-	4.56bcdef	50.4abc	221.1	293.1
Napier	4.0	4.7	+	+	-	4.62bcdef	52.8bcd	129.9	183.8
Rialto	3.0	3.0	+	+	-	3.93abcd	41.2ab	222.1	210.3
Savannah	4.0	4.3	+	+	-	4.20abcde	53.0bcd	168.1	199.0
Shamrock	3.3	2.7	+	+	-	4.83cdef	51.9abcd	267.2	348.0
P-Value (28 df)	<0.001	<0.001	-	-	-	<0.001	<0.001	<0.001	<0.001
SED	-	-	-	-	-	0.405	3.53	34.31	30.93

Table 3 Chambon sur Cisse 2002 (SBWMV+WSSMV)

Variety	Symptom severity (0-5) 11/04/02	Leaves positive (of 5) ELISA 25/04/02 SBWMV	WSSMV	TGW at 15% Humidity	Yield (t/ha) at 15% Humidity	Height (cm)	Emergence (plants/m²) 15/11/01	Number of heads/m² 02/07/02
Cezanne	5	5	3	39.6	5.28	75.0	144	259
Aardvark	1.0	2	0	50.9g	9.91	80.0f	179	327cd
Charger	0.0	1*	0	47.8efg	9.83	75.0ef	191	303bcd
Claire	0.0	1*	0	45.8ef	10.00	79.0f	206	304bcd
Hereward	0.0	1*	0	46.0ef	9.62	80.0f	165	292bcd
XI19	0.7	0	0	58.0h	9.28	90.0g	174	286bcd
Biscay	3.3	4	0	48.7fg	8.98	71.0de	214	305bcd
Consort	4.7	5	0	41.7bce	6.59	66.7cd	172	270bc
Deben	4.3	5	0	44.8de	7.13	79.7f	183	292bcd
Equinox	4.7	5	0	49.1fg	4.26	56.7a	152	201a
Malacca	4.7	4	0	39.9b	6.62	59.3ab	218	351d
Napier	4.7	4	0	46.2ef	6.89	66.0bcd	171	275bc
Option	5.0	5	0	36.1a	5.44	59.3ab	197	267bc
Savannah	5.0	5	0	44.3cde	5.83	63.3abc	184	250ab
Shamrock	3.7	5	0	41.1bc	6.87	58.7a	156	262abc
Tanker	5.0	5	0	46.1ef	6.76	58.3a	187	245ab
P-Value (28 df)	<0.001	-	-	<0.001	<0.001	<0.001	0.285	0.004
SED	-	-	-	1.61	0.549	3.11	24.4	28.7

* Weak positive.

Table 4 Landes Le Gaulois 2000 (WSSMV)

Variety	Symptom severity (0-5) 09/03/00	Symptom severity (0-5) 03/05/00	Leaves positive for WSSMV (of 5) by ELISA 27/03/00	Yield (t/ha) at 15% humidity	Height (cm)	Emergence (plants/m²) 26/09/99	Number of heads/m² 12/07/00
Aztec	0.0	0.0	0	6.30	77.3	265.7	533.3
Cezanne	4.7	5.0	5	5.03	82.3	262.3	414.7
Tremie	0.0	0.0	0	6.45	77.7	259.0	481.9
Aardvark	0.0	0.3	0	4.20abc	73.0a	289.7	389.2
Charger	0.0	0.0	0	5.76c	74.0ab	251.0	534.3
Claire	0.0	0.0	0	4.21abc	81.7bcd	236.7	435.3
Hereward	0.0	0.0	0	5.23abc	79.3abcd	252.7	507.4
Buster	0.0	0.0	0	5.30abc	75.3abc	212.0	419.1
Consort	0.0	0.0	0	4.93abc	77.0abcd	250.0	471.1
Equinox	0.0	0.0	0	3.87ab	72.0a	255.0	410.3
Madrigal	0.0	0.0	0	3.60a	72.3a	227.1	418.6
Malacca	0.0	0.0	0	5.06abc	78.3abcd	211.3	533.3
Napier	0.0	0.0	0	5.73bc	74.7abc	220.0	476.5
Reaper	0.0	0.0	0	3.81a	83.0cd	222.7	433.8
Rialto	0.7	0.0	0	5.16abc	84.7d	247.7	445.1
Riband	0.0	0.0	0	4.87abc	82.0bcd	239.7	389.2
Savannah	0.0	0.0	0	5.11abc	80.0abcd	273.3	409.3
Shamrock	0.0	0.0	0	5.38abc	76.3abcd	234.3	459.3
P-Value (28 df)	0.450	0.450	-	0.015	<0.001	0.009	0.009
SED	-	-	-	0.612	2.66	18.41	39.67

Table 5 Landes Le Gaulois 2002 (WSSMV)

Variety	Symptom severity (0-5) 12/03/02	Symptom severity (0-5) 17/04/02	Yield (t/ha) at 15% Humidity	TGW (g) at 15% Humidity	Height (cm)	Emergence (plants/m²) 15/11/01	Number of heads/m² 02/07/02
Cezanne	4.0	4.0	10.65	53.38	95.7	247	459
Aardvark	0.0	0.0	10.22cde	53.00	84.7cde	227	419
Charger	0.0	0.0	10.00cd	56.20	78.7ab	229	436
Claire	0.0	0.0	10.93efg	45.77	85.7cde	238	433
Hereward	0.0	0.0	9.07ab	45.93	86.7de	212	446
XI19	0.0	0.0	11.18g	52.70	96.3h	202	403
Biscay	0.0	0.0	11.10fg	50.33	90.7fg	241	471
Consort	0.7	0.0	10.02cd	46.63	85.0cde	232	458
Deben	0.0	0.0	10.64defg	51.13	93.0gh	202	465
Equinox	1.3	0.0	10.33cdef	53.47	78.3a	208	383
Malacca	0.0	0.0	10.09cd	44.43	85.0cde	220	482
Napier	1.3	0.0	10.31cdef	50.27	83.7cd	206	456
Option	1.3	0.0	10.24cde	44.53	88.0ef	196	427
Savannah	0.7	0.0	10.60defg	50.87	85.7cde	215	397
Shamrock	0.7	0.0	8.78a	44.53	82.0bc	239	481
Tanker	1.3	0.0	9.71bc	48.27	76.3a	232	390
P-Value (42 df)	0.126	-	<0.001	<0.001	<0.001	0.337	0.012
SED	-	-	0.355	0.642	1.67	19.71	28.20

Table 6 Ozzano 2000 (SBWMV)

Variety	Symptom severity (0-4) 18/04/00	SBWMV ELISA on leaves 27/03/00 (of 4 plots)	Yield (t/ha) at 13% humidity	Height (cm)
Grazia	0.75	4	3.67	83.5
Valnova	0.56	4	4.45	82.3
Aardvark	0.38	0	4.99bcd	70.5bcde
Charger	0.13	0	5.35d	69.0bcde
Claire	0.31	0	4.60abc	72.5de
Hereward	0.13	0	4.71abcd	70.5cde
Buster	0.19	1	4.65abcd	65.3abc
Consort	0.46	0	4.91bcd	66.3abcd
Equinox	0.19	0	5.15cd	67.3abcd
Madrigal	0.31	1	4.54abc	63.3ab
Malacca	0.19	0	4.70abcd	75.0ef
Napier	0.25	2	5.03cd	70.5cde
Reaper	0.13	0	4.89bcd	74.8ef
Rialto	0.25	2	4.81bcd	80.8f
Riband	0.69	1	3.95a	72.5de
Savannah	0.69	0	4.29ab	61.0a
Shamrock	0.00	0	5.11cd	71.0cde
P-Value (42 df)	0.107	-	<0.001	<0.001
SED	-	-	0.255	2.37

Table 7 Ozzano 2002 (SBWMV)

Variety	Symptom severity (0-4)		SBWMV ELISA on leaves (of 4 plots)	
	13/03/02	03/04/02	13/03/02	03/04/02
Grazia	3.9	3.2	3	4
Valnova	4.0	3.7	2	3
Aardvark	0.2	0.3	1	1
Charger	0.7	0.8	0	0
Claire	0.5	0.2	0	0
Hereward	0.0	0.0	0	0
X 119	0.1	0.4	0	0
Biscay	0.3	0.2	0	0
Consort	0.3	1.0	0	2
Deben	1.8	0.8	3	1
Equinox	2.5	1.9	1	2
Malacca	0.3	0.2	1	2
Napier	1.3	1.0	2	3
Option	1.0	1.4	2	3
Savannah	1.3	1.0	1	1
Shamrock	1.3	1.4	1	0
Tanker	2.2	1.8	2	1
P-Value (df 14)	0.006	0.047	-	-
SED	-	-	-	-

Table 8 Minerbio 2001 (SBWMV)

Variety	Symptom severity (0-4) 05/03/01	SBWMV ELISA on Leaves 21/03/01 (of 4 plots)	Yield (t/ha) at 13% humidity	Height (cm)
Grazia	2.75	4	3.80	72.5
Valnova	3.00	4	2.02	71.8
Aardvark	0.50	1	8.19gh	85.0bc
Charger	0.13	0	6.85ef	83.8bc
Claire	0.00	0	8.29h	92.5de
Cockpit	0.10	0	6.47de	112.5f
Hereward	0.25	0	6.24de	86.3cd
Buchan	1.00	2	7.34efgh	79.0ab
Consort	1.13	2	3.90b	79.5abc
Eclipse	1.19	1	7.27efgh	86.3cd
Equinox	0.94	3	7.78fgh	76.3a
Madrigal	0.63	2	6.71ef	78.6ab
Malacca	0.56	1	5.29cd	85.0bc
Napier	1.06	4	7.03efg	81.0abc
Rialto	0.38	1	6.20cde	96.3e
Savannah	0.88	1	4.99bc	82.0abc
Shamrock	0.06	1	2.56a	79.3ab
P-Value (42 df)	<0.001	0.05	<0.001	<0.001
SED	-	0.2321	0.395	2.27

Table 9 Minerbio 2002 (SBWMV)

Variety	Symptom severity (0-4)				Results for SBWMV ELISA (of 4 plots)		Yield (t/ha) at 13% Humidity	TGW (g) at 13% Humidity	Height (cm)	Heading date
	28/02/02	13/03/02	03/04/02	22/04/02	13/03/02	03/04/02				
Grazia	3.0	3.8	4.0	3.6	4	4	3.24	35.3	74.3	43.8
Valnova	2.3	3.3	3.5	3.4	4	4	2.43	39.9	70.8	37.3
Aardvark	0.2	0.0	0.4	0.6	0	0	5.30efg	30.7	80.0c	50.3
Charger	0.0	0.1	0.1	0.1	1	0	5.92g	29.3	78.8bc	48.5
Claire	0.1	0.1	0.0	0.0	0	0	4.84bcdef	26.0	84.8de	51.3
Hereward	0.1	0.1	0.3	0.3	0	0	4.89bcdef	27.1	80.0c	50.8
XI19	0.0	0.3	0.8	0.5	0	0	4.70bcdef	28.1	88.8fg	50.3
Biscay	0.0	0.4	0.3	0.1	0	0	6.03	31.0	87.5ef	51.3
Consort	0.3	0.5	1.5	0.4	0	0	3.13a	22.4	78.0bc	54.3
Deben	0.4	0.6	1.4	0.4	2	1	5.44fg	27.0	91.0g	51.3
Equinox	0.5	0.5	1.1	0.4	0	0	4.45bcdef	33.2	73.8a	51.3
Malacca	0.2	0.8	0.2	0.4	0	0	3.93ab	26.6	83.3d	50.5
Napier	0.8	1.0	1.1	0.4	0	0	5.12defg	30.5	78.0bc	50.3
Option	0.4	1.0	0.8	0.4	1	0	5.02cdefg	29.1	83.3d	51.0
Savannah	0.9	1.1	1.3	0.6	0	0	4.18bcd	26.4	77.3bc	54.0
Shamrock	0.2	0.1	0.3	0.3	0	0	4.06abc	26.6	78.3bc	50.3
Tanker	0.4	0.7	1.0	0.2	0	0	4.33bcde	29.3	76.5ab	53.3
P-Value (28 df)	0.002	0.018	0.001	0.402	-	-	<0.001	<0.001	<0.001	<0.001
SED	-	-	-	-	-	-	0.450	1.74	1.42	0.76

Table 10 Rome 2002 (SBWMV+WSSMV)

Variety	Symptom severity (0-4) 19/03/02	SBWMV ELISA (of 4 plots) 05/03/02	SBWMV ELISA (of 4 plots) 27/03/02	WSSMV ELISA (of 4 plots) 05/03/02	WSSMV ELISA (of 4 plots) 27/03/02	Yield (t/ha) at 13% Humidity	TGW (g) at 13% Humidity	Height (cm)	Heading date (days from 01/04)
Grazia	1.6	2	1	4	4	3.73	42.3	83.8	22.8
Valnova	1.3	4	2	4	4	3.33	48.4	81.3	16.5
Aardvark	0.6	0	2	0	0	5.24bc	43.2	75.0abc	35.5
Charger	0.3	0	1	0	0	6.05c	43.0	73.8ab	33.3
Claire	0.2	0	1	0	0	6.10c	41.0	80.0cde	39.8
Hereward	0.5	0	0	0	0	5.25bc	39.0	75.0abc	39.3
XI19	0.7	1	2	0	0	5.39bc	45.9	82.5de	35.3
Biscay	0.5	0	2	0	0	6.25c	43.7	80.0cde	37.3
Consort	0.7	0	0	0	0	3.93a	39.3	75.0abc	40.8
Deben	0.3	1	1	0	0	4.98abc	42.6	85.0e	39.0
Equinox	0.2	1	2	0	0	4.60ab	44.3	73.8ab	39.0
Malacca	0.5	0	1	0	0	5.08abc	39.3	77.5bcd	33.5
Napier	0.3	0	2	0	0	5.34bc	42.4	73.8ab	36.3
Option	0.3	0	1	0	0	5.27bc	36.8	77.5bcd	38.5
Savannah	0.5	0	1	0	0	5.00abc	42.6	75.0abc	39.0
Shamrock	0.3	0	1	0	0	5.07abc	39.8	71.3a	34.8
Tanker	0.5	0	2	0	0	4.34ab	39.9	72.5ab	38.5
P-Value (42 df)	0.011	-	-	-	-	0.005	<0.001	<0.001	<0.001
SED	-	-	-	-	-	0.535	0.84	2.53	1.173

Table 11 Simple correlation between grain yield (t/ha), symptom severity (0-5) on 03/05/01 and other plant characteristics for varieties grown at the site in Chambon sur Cisse, 2000.

	Mean	Range	Yield (t/ha)	Symptom severity (0-5)[†]
Height at harvest (cm)	60	41-82	0.772***	-0.765***
TGW (g)	43.5	36-51	0.078	-0.136
Plant emergence (m²)	254	202-323	0.251	-0.481***
Heads per m²	354	213-559	0.770***	-0.569***
Yield (t/ha)	5.68	1.51-9.42	-	-0.694***

P=0.05, ** P=0.01,*** P=<0.001

[†] Data correlation using Spearman's rank correlation

Table 12 Simple correlation between grain yield (t/ha), symptom severity (0-5) on 29/03/01 and other plant characteristics for varieties grown at the site in Chambon sur Cisse, 2001.

	Mean	Range	Yield (t/ha)	Symptom severity (0-5) [†]
Height at harvest (cm)	56	33-85	0.799***	-0.748***
TGW (g)	44	37-53	0.318*	-0.494***
Plant emergence (m²)	218	116-297	0.124	-0.024
Heads per m²	245	71-375	0.669***	-0.608***
Yield (t/ha)	4.58	2.47-6.66	-	-0.788***

P=0.05, ** P=0.01,*** P=<0.001

[†] Data correlation using Spearman's rank correlation

Table 13 Simple correlation between grain yield (t/ha), symptom severity (0-5) on 11/03/02 and other plant characteristics for varieties grown at the site in Chambon sur Cisse, 2002.

	Mean	Range	Yield (t/ha)	Symptom severity (0-5) [†]
Height at harvest (cm)	69	53-90	0.737***	-0.714***
TGW (g)	45	35-59	0.523***	-0.494**
Plant emergence (m²)	183	116-250	0.117	0.105
Heads per m²	282	179-378	0.572***	-0.392**
Yield (t/ha)	7.60	3.43-10.80	-	-0.857***

P=0.05, ** P=0.01,*** P=<0.001

[†] Data correlation using Spearman's rank correlation