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# The Evaluation of Wheat Cultivar Resistance and Yield Loss Thresholds in Response to Barley Yellow Dwarf Virus-PAV Infection

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**Abstract:** The PAV strain of barley yellow dwarf virus (BYDV) is one of the causal agents of yellow dwarf disease in cereals. The use of germplasm resistant to BYDV is generally regarded as the most effective means of controlling damage caused by this pathogen. In field trials, response to infection with a barley yellow dwarf virus of selected wheat cultivars registered in the Czech Republic was compared with that of control cultivars. Although a good level of resistance to BYDV-PAV was found in cultivar Athlon and yield loss was low, symptoms were more severe than on the moderately resistant control cultivar Sparta. Several other cultivars, such as Nordika, Julie, and Replik, also had slightly less than a 30% reduction in grain weight per spike, even though symptoms were more severe on Sparta or Athlon. Our results showed that, in the case of approximately 60% of wheat plants with BYDV-PAV symptoms, the yield reductions under optimal agronomic conditions reached approximately 17% for moderately resistant cultivars and 30% for moderately susceptible cultivars. The application of N fertilizer significantly reduced yield losses in BYDV-PAV-infected wheat cultivars, particularly in the moderately resistant cultivars. Even when infected with BYDV-PAV, the yield of moderately resistant cultivars, including those of spring wheat, was still acceptable. However, the re-cultivation costs of spring wheat in replacing damaged winter wheat lead to a total economic loss per hectare that is much greater than that for BYDV-infected wheat cultivars (moderately resistant and/or moderately susceptible ones). Furthermore, the economic loss is much lower when a moderately resistant cultivar is used. Hence, even with a high level of disease symptoms in winter wheat, the re-cultivation of spring wheat is not economically feasible.

**Keywords:** BYDV; PAV; cultivar; VSSs (visual symptom scores); GWS-R (reduction in grain weight per spike); N fertilizer

## 1. Introduction

Wheat, which is the main crop in the Czech Republic, is grown on approximately 1.5 million hectares. Barley yellow dwarf viruses (BYDVs), which comprise a group of species and strains, are the causal agents of yellow dwarf disease in cereal crops, including wheat [1]. This disease can cause significant yield losses [2] as a result of root and shoot dwarfing and leaf yellowing [3]. BYDVs are ssRNA viruses belonging to the genera *Luteovirus* (BYDV strains PAV, PAS, MAV, and Kerll) and *Polerovirus* (cereal yellow dwarf virus-RPV, maize yellow dwarf virus-RMV) and of unassigned stains (BYDV-SGV and BYDV-GPV) in the family Luteoviridae (ICTV 2018). Strains PAV, PAS, and MAV of BYDV have been found in infected cereal crops and grasses in the Czech Republic [4], with a prevalence of PAV in crop species (wheat, barley) and PAS in volunteer cereals and grasses [5]. BYDVs are transmitted by more than 25 species of aphids [6]. The most abundant vectors of the virus in the Czech Republic include *Sitobion avenae*, *Rhopalosiphum padi*, *R. maidis*, and *Metopolophium dirhodum* [5]. The incidence of BYDV in winter in winter cereals is usually high, and the associated crop losses are a serious concern for growers. The disease severity is usually less pronounced in wheat cultivars than in barley cultivars [7].

Host resistance is classified into two categories: tolerance (symptoms and yield losses are reduced, though virus multiplication is not altered) and resistance (virus multiplication and spread are significantly reduced) (for a review, see Reference [8]). Resistant or tolerant wheat cultivars is essential for sustainable crop control against BYDV infection [9]. Thus far, four resistance genes, *Bdv1* [10], *Bdv2* [11], *Bdv3* [12], and *Bdv4* [13], have been reported in wheat, but the introduction of these genes in commercial cultivars has not been effective [14,15]. Furthermore, evaluation of resistant sources carrying the *Bdv1* and *Bdv2* genes suggests a polygenic nature for BYDV resistance [16]. The only exception from other genes is *Bdv1*, which originated from the Brazilian spring cultivar Frontana that confers tolerance to BYDV-MAV [17]. Several wheat cultivars apparently have a certain level of resistance that is associated with mild symptoms and low yield reductions (for a review, see Reference [9]).

The purpose of the present study was to: (i) study the level of BYDV-PAV resistance in winter wheat cultivars grown in Central Europe. (ii) report on the influence of cultivar resistance on yield losses and qualitative variables of wheat grains as well as the impact of nutrient applications on yield improvements when the rate of virus infection is high, and (iii) determine the thresholds for yield losses of wheat cultivars associated with the BYDV-PAV infection.

## 2. Materials and Methods

### 2.1. Assessment of Wheat Cultivar Resistance against BYDV-PAV

The resistance of 24 winter wheat cultivars to BYDV infection was evaluated in small-plot field trials (0.5 $m^2$) in Prague-Ruzyně (50°05′05.4″ N, 14°17′59.9″ E) from 2015–2017. The mean temperature was 8 °C, and total rainfall was 472.8 mm. Resistant cv. PSR 3628, moderately resistant cv. Sparta, moderately susceptible cv. Vlada, and the susceptible breeding line SG-S 27-03 were chosen as the control checks based on earlier studies [16,18]. The plants were grown in double-row, 1-m-long plots, with two replications (22 cm row spacing, 6 cm within the row). Infected variants of the plants (with two replications) were inoculated (at the start of tillering) by viruliferous *R. padi* reared in a greenhouse, as described elsewhere [7,19]. After a 5–7 day inoculation access period (IAP), the aphids were killed by an insecticide (Perfekthion, BASF, Ludwigshafen, Germany). The second uninfected variant (one replication) was protected by a special fabric during the IAP of the inoculated variant. Plants were confirmed to be infected with BYDV-PAV using enzyme-linked immunosorbent assays (ELISAs) [20] using a DAS-ELISA (double antibody sandwich ELISA) kit (SEDIAG, Bretenière, France) when needed.

Symptoms of BYDV-PAV infection were evaluated at the flowering stage using the 0–9 scale described by Schaller and Qualset [21] (Table 1).

**Table 1.** Symptoms rating scale based on Schaller and Qualset [21].

| Rating Scale | Symptoms |
|---|---|
| **0** | No visible symptoms |
| **1** | Trace amounts of yellowing, vigorous plant appearance |
| **2** | Restricted yellowing of leaves, more leaves discolored |
| **3** | Moderate to low amount of yellowing, no sign of dwarfing or reduction in tillering |
| **4** | Moderate to somewhat extensive yellowing, no dwarfing; moderate to good plant vigor |
| **5** | More extensive yellowing, moderate to poor plant vigor, some dwarfing |
| **6** | High level of yellowing, poor plant vigor, apparent dwarfing |

**Table 1.** *Cont.*

| Rating Scale | Symptoms |
|---|---|
| **7** | Severe yellowing, small spikes, moderate dwarfing, poor plant appearance |
| **8** | Nearly complete yellowing of all leaves, dwarfing, tillering apparently reduced (rosette appearance), reduced spike size with some sterility |
| **9** | Marked dwarfing, complete yellowing, few or no spikes, considerable sterility, forced maturity or drying of the plant before normal maturity is reached |

Visual symptom scores (VSSs) were calculated in 100 plants. The grain weight per spike (GWS) and percentage reduction in grain weight per spike (GWS-R) were assessed at harvest using 30 randomly selected spikes from the stand in each of the infected and control plots.

### 2.2. *Evaluation of the Effects of BYDV-PAV Infection on Yield and Qualitative Parameters*

The effects of BYDV-PAV infection on the yield and qualitative traits of wheat grains related to varietal resistance were evaluated in field trials at Stupice (50°03′07.6″ N 14°38′45.5″ E) for 3 years (2014–2016) using three cultivars with contrasting resistance: moderately resistant Meritto [16], moderately resistant/moderately susceptible Diadem, and susceptible SG-S 27-03 [16]. Each genotype was sown in 12 randomized repeats, and each plot was 10 square metres. One-half of the 36 plots were infected with BYDV-PAV (1), and the other half were not (0). The inoculation with BYDV-PAV was carried out by greenhouse-reared viruliferous *R. padi* aphids at the three-leaf stage until the start of tillering. The estimated rate of BYDV-PAV infection based on the presence/absence of visual symptoms (dwarfing, leaf discolorations) in individual plants ranged from 60% to 85%.

One-third of each infection variant was treated only with basic NPK fertilizer (120-36-85) (UNTR). NPK fertilizer contains three macronutrients: nitrogen (N), phosphorus (P), and potassium (K). Second third of each infection variant was treated with basic NPK fertilizer and with 1–2 fungicides as needed (FUNG). The last third was treated with an increased dose of NPK (145-40-85) and with fungicide (FUNG + FERT). All plants received insecticidal treatment to limit undesired BYDV-PAV infection. Symptoms were rated at the flowering stage on a scale. The 0–9 scale was described (0 represents no symptoms, and 9 represents the highest severity [21]), and visual symptom scores (VSSs) were assessed. Plants were then harvested to measure grain yield, test weight, and protein content. The test weight and protein content were measured by near-infrared spectroscopy (type of analyser: NIRS, FOSS Infratec NOVA).

### 2.3. *Statistical Analysis*

Each experiment was setup in randomized repeats (see Sections 2.1 and 2.2) and results were expressed as mean ± standard error (SE). The data were analysed using the statistical analysis package Statistica 13.3 (Statsoft Inc., Tulsa, OH, USA). A general factorial ANOVA (Analysis of variance) at a 95% confidence interval and 5% level of significance was used. When the $p$-value was less than 0.05, the Fisher's Least Significant Difference (LSD) test for multiple comparisons were carried out. The significantly different mean values were represented by different letters.

In the first experiment (Section 2.1), a factorial ANOVA with two independent factors (cultivar and year) was used for variables visual symptom scores (VSSs) and percentage reduction in grain weight per spike (GWS-R). The statistical model was used without interactions of the cultivar per year because some cultivars were not tested in 2017.

In the second experiment (Section 2.2), a factorial ANOVA with four independent factors (BYDV infection, cultivar, treatment, and year) was carried out for variables yield, test weight, and protein content. The interactions cultivar × BYDV, cultivar × treatment, and treatment × BYDV were included in the statistical model.

## 3. Results

### *3.1. Assessment of Wheat Cultivar Resistance Against BYDV-PAV*

Statistically significant differences in BYDV-PAV infection were proved among tested winter wheat cultivars by Analysis of Variance (ANOVA) (Table 2). The responses of winter wheat cultivars to field infection with BYDV-PAV are shown in Table 3. The average visual symptom score value ranged from 1.25 to 7.25, and the percentage reduction in grain weight per spike ranged from 4.96 % to 59.74%. The resistant control PSR 3628 had the highest resistance level (few symptoms, 1.25, low yield reduction, 4.96%). Sparta had moderate resistance (VSSs, 4.5) and yield reduction (18.8%). Cultivars Athlon, Nordika, Julie, Rumor and Replik had a yield reduction less than 30% (24.17% to 29.17%), but symptoms were more severe (VSSs score 5.17 to 6.25) than on the control cultivar Sparta. The susceptible control line SG-S 27-03 line had the highest yield reduction (59.74%) and most severe symptoms (7.25).

**Table 2.** Results of analyses of variance (*F*-value) for visual symptom scores (VSSs) and grain weight per spike (GWS-R).

| Effect | SS | Df | MS | *F*-Ratio | *p*-Value |
|---|---|---|---|---|---|
| **VSSs** | | | | | |
| Intercept | 2808.652 | 1 | 2808.652 | 9004.891 | 0.000000 |
| CULTIVAR/LINE | 151.296 | 27 | 5.604 | 17.966 | 0.000000 |
| YEAR | 21.831 | 2 | 10.916 | 34.997 | 0.000000 |
| Error | 31.502 | 101 | 0.312 | | |
| **GWS**-R | | | | | |
| Intercept | 109028.473 | 1 | 109028.473 | 962.295 | 0.000000 |
| CULTIVAR/LINE | 14867.223 | 27 | 550.638 | 4.860 | 0.000000 |
| YEAR | 3224.314 | 2 | 1612.157 | 14.229 | 0.000004 |
| Error | 11443.350 | 101 | 113.300 | | |

SS = Sum of Squares, Df = Degrees of Freedom, MS = Mean Square.

### *3.2. Evaluation of the Effects of BYDV-PAV Infection on Yield and Qualitative Traits*

BYDV-PAV infection had a statistically significant effect on wheat yield, test weight, and grain protein content (Table 4). Statistically significant differences between tested cultivars were proved in these three previously mentioned variables. The treatment with fungicide and NPK fertilizer was significant for yield and test weight, not for protein content. Virus infection decreased yield and test weight, but protein content increased in the variant infected with BYDV-PAV. The highest protein content was detected in the variant infected with the virus (1—FUNG, UNTR) without an increased dose of NPK (Table 5) while the highest yield was detected in the variant without infection (0—FUNG + FERT) treated by fungicide and NPK fertilizer. The yield reduction caused by BYDV-PAV infection was 20% on average. Test weight was statistically, significantly higher in an uninfected variant, but was no longer affected by fungicide application or fertilization. The positive effect of fungicide on the increase in yield and test weight has been demonstrated in both cases in the infected variant. The application of fungicides and fertilizers is of great importance for reducing the negative effects on yield in BYDV-PAV-infected wheat crops. The highest visual symptoms score (VSSs) was observed in line SG-S27-03 (5.2), and relatively low symptom ratings were recorded for the moderately resistant cultivar Meritto (3.1). The uninfected variant lacked symptoms. Figure 1 presents the yields of the tested cultivars with respect to the infected and uninfected variants with different types of additional treatment. As documented, the highest yield potential was shown for Diadem (11.1 t/ha, 0—FUNG + FERT), but Meritto achieved a relatively higher yield (9.6 t/ha) in the infected variant (1—FUNG + FERT) due to a higher degree of BYDV-PAV resistance. Line SG-S27-03 had the lowest yield in both the infected and uninfected variants, as this line represents an older material that is susceptible to

BYDV-PAV. The effect of N addition in this line was more pronounced in the infected variant than in the uninfected variant.

**Table 3.** Evaluation of the resistance of winter wheat cultivars after BYDV-PAV infection in three-year trials in Prague-Ruzyně from 2015 to 2017.

| | VSSs (0–9)/GWS-R (%) | | | | |
|---|---|---|---|---|---|
| **Cultivar/Line** | **2015** | **2016** | **2017** | **Average** | **H. g.** |
| PSR 3628 | 1.75/14.87 | 1.00/0.00 | 1.00/0.00 | 1.25/4.96 | a/a |
| Sparta | 3.50/20.70 | 5.50/18.95 | 4.50/15.95 | 4.50/18.80 | b/b |
| Bonanza | 4.25/19.24 | 5.50/46.21 | 4.75/34.61 | 4.83/33.35 | bc/bcdef |
| Tilman | 3.75/42.58 | 6.25/40.96 | nt/nt | 5.00/41.77 | bcd/defg |
| Tosca | 4.50/34.06 | 5.50/28.02 | nt/nt | 5.00/31.04 | bcd/bcde |
| Faunus | nt/nt | 6.00/57.88 | 4.25/16.54 | 5.13/37.21 | bcd/cdefg |
| Replik | 4.50/24.72 | 6.50/13.98 | nt/nt | 5.17/29.17 | bcde/bcde |
| Annie | 4.50/27.18 | 6.00/40.30 | nt/nt | 5.25/33.74 | bcde/bcdefg |
| Bernstein | 5.50/29.53 | 5.75/50.61 | 4.50/27.13 | 5.25/35.76 | bcde/cdefg |
| Frisky | 4.75/25.91 | 6.00/51.38 | 5.00/17.49 | 5.25/31.60 | bcde/bcde |
| Pankratz | 5.25/25.38 | 5.75/37.04 | 4.75/34.56 | 5.25/32.33 | bcde/bcde |
| Rumor | 4.50/18.09 | 6.00/35.98 | nt/nt | 5.25/27.03 | bcde/bcd |
| Sailor | 4.50/33.20 | 6.00/44.94 | nt/nt | 5.25/39.07 | bcde/cdefg |
| Artist | 5.00/36.28 | 5.75/47.29 | nt/nt | 5.38/41.78 | bcde/defg |
| Athlon | 5.00/30.76 | 5.75/17.57 | nt/nt | 5.38/24.17 | bcde/bc |
| Julie | 4.75/20.82 | 6.00/33.51 | nt/nt | 5.38/27.17 | bcde/bcd |
| Balitus | 5.50/39.08 | 6.00/56.39 | 5.00/13.19 | 5.50/36.22 | cde/cdefg |
| Florus | 5.00/17.74 | 6.00/49.93 | nt/nt | 5.50/33.84 | cde/bcdefg |
| RGT Matahari | 5.25/35.22 | 6.00/33.21 | 5.25/31.40 | 5.50/33.28 | cde/bcdef |
| Partner | nt/nt | 5.75/48.85 | 5.50/50.63 | 5.63/49.74 | cde/gh |
| Genius | 5.50/33.56 | 6.00/34.76 | nt/nt | 5.75/34.16 | cdef/cdefg |
| Vlada | 6.00/36.94 | 6.00/50.23 | 5.50/45.80 | 5.83/44.33 | def/efg |
| Grizzly | 5.50/31.21 | 6.25/36.58 | nt/nt | 5.88/33.90 | def/bcdefg |
| Tobak | 6.00/44.64 | 6.00/52.44 | nt/nt | 6.00/48.54 | defg/fgh |
| Nordika | 6.50/27.62 | 6.00/26.52 | nt/nt | 6.25/27.07 | efg/bcd |
| Gordian | 6.50/33.11 | 7.00/52.44 | nt/nt | 6.75/42.78 | fgh/defg |
| Avenue | 6.50/22.94 | 7.50/47.39 | nt/nt | 7.00/35.17 | gh/cdefg |
| SG-S 27-03 | 7.25/62.44 | 7.25/50.00 | 7.25/66.78 | 7.25/59.74 | h/h |
| Average | 5.06a/30.30a | 5.89b/39.41b | 4.77a/29.51a | 5.40/34.37 | |

nt = not tested, H. g. = Homogeneous groups for two variables: VSSs (visual symptom scores), GWS-R (reduction of grain weight per spike). The significantly different mean values were represented by different letters a-h ($p = 0.05$, Fisher's LSD test).

**Table 4.** Results of analyses of variance (F-value) for protein content, yield, and test weight.

| Protein Content | SS | DF | MS | *F*-Ratio | *p*-Value |
|---|---|---|---|---|---|
| Intercept | 17421.15 | 1 | 17421.15 | 25618.86 | 0.000000 |
| Year | 273.59 | 2 | 136.80 | 201.17 | 0.000000 |
| Treatment | 2.69 | 2 | 1.34 | 1.98 | 0.144296 |
| Cultivar | 9.76 | 2 | 4.88 | 7.18 | 0.001267 |
| BYDV | 10.25 | 1 | 10.25 | 15.08 | 0.000194 |
| Treatment × cultivar | 6.69 | 4 | 1.67 | 2.46 | 0.050852 |
| Treatment × BYDV | 2.98 | 2 | 1.49 | 2.19 | 0.117260 |
| Cultivar × BYDV | 2.13 | 2 | 1.06 | 1.56 | 0.214864 |
| Error | 62.56 | 92 | 0.68 | | |
| Yield | | | | | |
| Intercept | 8884.884 | 1 | 8884.884 | 6531.290 | 0.000000 |
| Year | 95.216 | 2 | 47.608 | 34.997 | 0.000000 |
| Treatment | 28.852 | 2 | 14.426 | 10.604 | 0.000072 |

**Table 4.** *Cont.*

| Protein Content | SS | DF | MS | *F*-Ratio | *p*-Value |
|---|---|---|---|---|---|
| Cultivar | 13.979 | 2 | 6.989 | 5.138 | 0.007668 |
| BYDV | 103.663 | 1 | 103.663 | 76.203 | 0.000000 |
| Treatment × cultivar | 1.327 | 4 | 0.332 | 0.244 | 0.912653 |
| Treatment × BYDV | 3.466 | 2 | 1.733 | 1.274 | 0.284628 |
| Cultivar × BYDV | 2.040 | 2 | 1.020 | 0.750 | 0.475406 |
| Error | 125.153 | 92 | 1.360 | | |
| Test weight | | | | | |
| Intercept | 675,899.3 | 1 | 675,899.3 | 455,276.0 | 0.000000 |
| Year | 426.2 | 2 | 213.1 | 143.5 | 0.000000 |
| Treatment | 10.9 | 2 | 5.4 | 3.7 | 0.029459 |
| Cultivar | 110.3 | 2 | 55.1 | 37.1 | 0.000000 |
| BYDV | 42.4 | 1 | 42.4 | 28.6 | 0.000001 |
| Treatment × cultivar | 11.0 | 4 | 2.7 | 1.8 | 0.126427 |
| Treatment × BYDV | 6.7 | 2 | 3.4 | 2.3 | 0.109144 |
| Cultivar × BYDV | 0.3 | 2 | 0.2 | 0.1 | 0.889468 |
| Error | 136.6 | 92 | 1.5 | | |

SS = Sum of Squares, Df = Degrees of Freedom, and MS = Mean Square.

**Table 5.** Effects of treatment on protein content, grain yield, and test weight in infected and uninfected variants with BYDV-PAV.

| Variable | Treatment | BYDV | Average | H. g. |
|---|---|---|---|---|
| PROTEIN CONTENT | FUNG | 0 | 12.36582 | a |
| | FUNG + FERT | 0 | 12.40240 | a |
| | UNTR | 0 | 12.40943 | a |
| | FUNG + FERT | 1 | 12.55283 | a |
| | UNTR | 1 | 13.20334 | b |
| | FUNG | 1 | 13.27017 | b |
| YIELD | UNTR | 1 | 7.33339 | a |
| | FUNG | 1 | 7.98691 | b |
| | FUNG + FERT | 1 | 8.95098 | c |
| | FUNG | 0 | 9.74385 | d |
| | UNTR | 0 | 9.79630 | d |
| | FUNG + FERT | 0 | 10.60941 | e |
| TEST WEIGHT | UNTR | 1 | 77.81233 | a |
| | FUNG | 1 | 78.43879 | b |
| | FUNG + FERT | 1 | 79.19692 | c |
| | UNTR | 0 | 79.68244 | d |
| | FUNG | 0 | 79.68357 | d |
| | FUNG + FERT | 0 | 79.84349 | d |

The significantly different mean values were represented by different letters a–e ($p$ = 0.05, Fisher's LSD test). 1 = BYDV-PAV infection, 0 = uninfected control, UNTR = treated only with basic NPK fertilizer, FUNG = treated with basic NPK fertilizer and with 1–2 fungicides, and FUNG + FERT = treated with an increased dose of NPK and with fungicide.

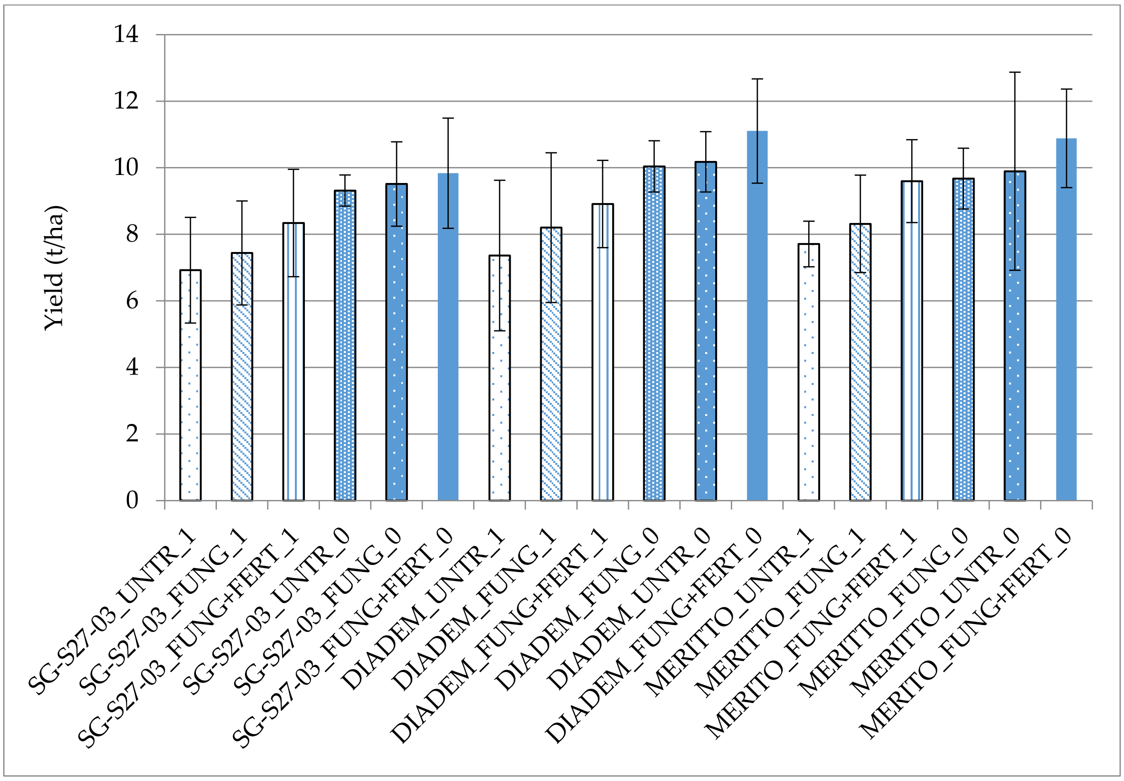


**Figure 1.** Grain yield for wheat cultivars infected with BYDV-PAV and treated with N. Cultivars: SG-S 27-03, susceptible to BYDV-PAV. Diadem, moderately resistant/moderately susceptible. Meritto, moderately resistant. Bars on each column are standard error. 1 = BYDV-PAV infection, 0 = uninfected control. UNTR = treated only with basic NPK fertilizer. FUNG = treated with basic NPK fertilizer and with 1–2 fungicides. FUNG + FERT treated with an increased dose of NPK and with fungicide.

### *3.3. The Economic Effects of BYDV-PAV Infection*

In approximately 60% of the wheat plants with BYDV-PAV symptoms, the yield reduction under optimal agronomic conditions reached approximately 17% for the moderately resistant cultivar and 30% for the moderately susceptible cultivar (Table 6). Even with BYDV-PAV infection, the yield of the moderately resistant cultivars, including those of spring wheat, was still acceptable. When we calculate the re-cultivation costs of spring wheat, then the total economic loss per hectare is much higher than that derived from virus infection.

**Table 6.** Evaluation of economic thresholds of winter wheat cultivars due to BYDV-PAV infection compared with spring wheat cultivars.

| **Threshold** | **Winter Wheat (on Average)** | **Winter Wheat Cultivar Meritto (Moderately Resistant) Infected with BYDV-PAV** | **Winter Wheat Cultivar Diadem (Moderately Susceptible) Infected with BYDV-PAV** | **Spring Wheat** |
|---|---|---|---|---|
| Yield (t $ha^{-1}$) | 6.0 | 4.98 | 4.2 | 5.4 |
| Percent of yield loss compared with non-infected plants (variants) | 0 | 17 | 30 | 10 |
| Yield by commodity price in the Czech Republic (€ $ha^{-1}$, average price of wheat per ton: 133 € $t^{-1}$) | 800 | 664 | 560 | 667 |
| Re-cultivation cost (€ $ha^{-1}$) | | | | 202 |
| Economic loss (€ $ha^{-1}$) | 0 | 136 | 240 | 465 |

## 4. Discussion

Disease severity is usually less pronounced in wheat cultivars than in barley cultivars [7], but our evaluation suggests that the current cultivars of winter wheat do not have a high level of resistance against BYDV-PAV. Attainment of resistance equal to the level exhibited by the moderately resistant cultivar Sparta is considered beneficial. Yield reduction for cultivar Athlon approached the level of Sparta. Previously, yield reduction for cultivars Elan and Matylda [7] was similar to that for Sparta. Due to the lack of resistance sources, the emphasis for breeding has been mainly to eliminate materials showing susceptibility at the level of the control cultivar (SG-S27-03) used in this scenario. With respect to agricultural practice, detecting and culling susceptible cultivars is particularly important. Cultivation of such cultivars carries a risk from epidemics of BYDV-PAV. Cultivars with a level of susceptibility similar to that of the control in this set were not identified. Among cultivars of winter wheat, it is difficult to find one with a high level of resistance at both the symptom level and the yield level. Among recently tested cultivars, only Elan has a low level yield reduction and BYDV-PAV symptoms [7]. In the present study, yield reduction was demonstrated for cultivar Athlon. Yield reductions were slightly lower for several other cultivars, such as Nordika, Julie, and Replik (less than 30% GWS-R). However, symptoms were rather severe, and greater than those on Sparta. These results again suggest that the evaluation of wheat resistance to BYDV-PAV based on symptoms is not effective and that analysis of GWS-R [7] and/or reduction in biomass [22] is necessary for a reliable evaluation of resistance. Quantifying virus titre analysis by using RT-qPCR can also be used to enhance the efficiency of resistance evaluation of wheat cultivars to BYDV-PAV and PAS [5].

Yields resulting in the trials showed that, in the case of BYDV-PAV infection, the use of cultivars resistant to BYDV is an effective means of controlling damage. The addition of nutrients improved the performance of the moderately resistant cultivar Meritto. Subsequent treatment with N can significantly reduce the yield loss, and the nutrient intake is hindered by weakened root systems [23]. On the basis of our results, during a BYDV-PAV epidemic, the most promising approach is clearly the use of moderately resistant cultivars supported by good cultivation conditions, such as the application of fungicides followed by N nutrients. Considering our results, we can assume that the moderately resistant cultivars will have an advantage during an epidemic of BYDV-PAV. However, the nutrient (and fungicide) treatment helped to statistically increase the yield of even the susceptible line SG-S 27-03. When the level of BYDV-PAV infection in wheat is high, the economic impact of yield is significant. The re-cultivation of spring wheat instead of winter wheat carries an even higher economic disadvantage (Table 6).

The highest protein content was detected in the variant infected with BYDV-PAV (1) in plots treated with fungicides (FUNG) and in untreated plots (UNTR) (Table 5). The relative protein levels in virus-infected wheat grain increase as a result of reduced translocation and reduced starch accumulation in the grain [24]. Grain protein content, which is a key factor in wheat quality, is associated with N uptake and is, therefore, affected by treatment with N fertilizer [25,26]. Moreover, seasons have particularly strong effects on grain and protein yields, and grain yield is often negatively correlated with protein content [25].

## 5. Conclusions

The productivity of wheat is a great economic concern for farmers, and the range of yield loss caused by BYDV-PAV infection (disease damage in general) should go hand in hand with calculations of economic losses. In this paper, we showed that the cultivation of moderately resistant cultivars could be an effective measure, even during virus infection, when supported by appropriate nutrients and fungicides. The yield losses could be considerably lower and still be acceptable to growers.

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