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Susceptibility of winter wheat cultivars to wheat ear insects in Central Germany

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Abstract The intensity of thrips and wheat blossom midges (WBM) infestations in twelve wheat cultivars was evaluated at the Plant Breeding Station, Silstedt, central Germany in 2008 & 2009 growing crop seasons. The research aimed at selecting the least infested cultivar to be profitably used in the forthcoming cultivation. Infestation levels were studied in flowering and milky stages (GS 65 and 73) of each cultivar in every single-spikelet in sample of 10 ears in both years.

There were significant differences in thrips and (WBM) densities among different cultivars in both years. Thrips numbers were the highest in Türkis, Global and Esket cultivars, while the lowest values were recorded in Robigus, Brompton and Carenius. The results showed that the highest WBM infestation was observed in Türkis, Tommi and Potenzial; on the other hand the lowest WBM infestation was found in some insect resistant cultivars (Brompton, Skalmeje, Robigus, Welford and Glasgow). The infested ears were positively correlated with the numbers of WBM among cultivars. The obtained results would give a good guide for choosing the proper cultivars which proved highly resistant to their specific pests.

Keywords Winter wheat cultivars · Insect resistance · Wheat blossom midge · Thrips · Silstedt

Anfälligkeit von Winterweizensorten gegenüber Weizengallmücken und Thripsen in Mitteldeutschland

Zusammenfassung Die Weizengallmücken *Sitodiplosis mosellana* (Géhin) und *Contarinia tritici* (Kirby) sowie die Thripsarten *Limothrips cerealium* (Halieus) und *L. denticornis* (Halieus) zählen zu den wichtigsten Schadinsekten am Getreide. Das mitteldeutsche Trockengebiet wurde durch die Zuchtstation der RAGT 2n Silstedt (12 Sorten) repräsentiert. In der vorliegenden Arbeit wurden in den Jahren 2008 und 2009 in Freilandversuchen untersucht, welchen Einfluss die Koinzidenz (Zusammentreffen der Mücken mit dem sensiblen Entwicklungsstadium des Weizens) auf das Schadausmaß nimmt. Zum Einsatz kam die Methode der Ährenuntersuchung. Der Befall wurde in der Blüte und Milchreife des Getreides (BBCH 65 und 73) untersucht. Von jeder Prüfsorte wurden in jedem Jahr 10 Ähren auf Befall mit Weizengallmückenlarven und Thripsen untersucht.

Es zeigten sich signifikante Unterschiede bei den Befallswerten von Weizengallmücken und Thripsen zwischen den Prüfsorten in beiden Jahren. Die Sorten Türkis, Global und Esket waren am stärksten mit Thripsen besiedelt (4.5, 4.3 und 4.1 Thripse/Ähreteil), während die Sorten Robigus und Carenius geringe Befallswerte aufwiesen (2.0 und 1.9 Thripse/Ähreteil). Die Ergebnisse zeigen, dass der höchste Befall mit Weizengallmückenlarven in der Sorte Türkis, (5.3 Larvae/Ähreteil) zu beobachten war. Die niedrigsten Befallswerte zeigten die resistenten Sorten (Brompton, Skalmeje, Robigus, Welford und Glasgow). Die Resultate belegen eine positive Korrelation zwischen den befallenen Ähren und den Zahlen der Weizengallmückenlarven pro Ähre. Im Rahmen dieser Arbeit konnten Sorten ermittelt werden, die geringe Befallswerte zeigen und somit geeignet sind in der landwirtschaftlichen Praxis dazu bei-

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zutragen Ertragsverluste zu vermindern und den Einsatz von Pflanzenschutzmitteln auf ein notwendiges Maß zu beschränken.

Schlüsselwörter Winterweizensorten · Insektenresistenz · Weizengallmücken · Thripse · Silstedt

Introduction

Globally, wheat (*Triticum* spp.) production exceeds that of all other cereal crops. Germany is the eighth largest producer of wheat in the world, averaging an annual production of 19,203 TMT (USDA 2007). Plant breeders have so far been unable to locate complete resistance to pests in any of the wheat cultivars, some of which otherwise have shown varying degree of immunity against many insects (Berzonsky et al. 2002; McKenzie et al. 2002). Wheat midges and thrips are the major insect pests of wheat ears.

The wheat midge, *Sitodiplosis mosellana* (Géhin) (Diptera: Cecidomyiidae), is an important pest of winter wheat, *T. aestivum* L., in Germany (Volkmar et al. 2008; Gaafar et al. 2009) and UK (Oakley et al. 1998) and Canada (Lamb et al. 2003). It coexists with the lemon wheat blossom midge, *Contarinia tritici* (Kirby) another gall midge that attacks the wheat head, (Kurppa 1989; Harris et al. 2003). Management strategies that include host plant resistance would help to minimize the economic and environmental impact of *S. mosellana* (Olfert et al. 2009).

Resistance to the wheat midge is partially dominant due to expression of the *Sm1* resistance as single gene (McKenzie et al. 2002), that mediates an induced hypersensitive response in the surface of developing seeds where wheat midge larvae begin feeding, resulting in larval death (Ding et al. 2000; Lamb et al. 2000a). In the wheat midge, the resistance act as an antibiotic reaction that includes elevation of phenol compound levels and results in the death of the young larvae shortly after they begin feeding (Ding et al. 2000; Harris et al. 2003). The adaptations that have been studied so far in the wheat midges have been due to alleles, usually completely or incompletely recessive, at single gene in the insects (Harris et al. 2003). Smith et al. (2007) stated that the density of wheat midge larvae developing on resistant wheat was lower compared to that of larvae developing on susceptible wheat cultivars and also mentioned that small numbers of larvae of *S. mosellana* matured in wheat cultivar were carrying the *Sm1* gene. It was also reported that wheat midge infestation was associated with a reduced proportion of well-formed wheat seeds and yield losses (Lamb et al. 2000b; Doane and Olfert 2008).

Thrips fauna can also cause serious damage to winter wheat (Volkmar et al. 2009), and current methods of control are not sufficient to prevent crop damage. The widespread thrips species; *Limothrips denticornis* (Hal.), *L. cerealium* (Hal.), *Haplothrips tritici* (Kurd.), *H. aculeatus* (Fab.), *Frankliniella tenuicornis* (Uzel) and *Thrips angusticeps* (Uzel) were recorded on different wheat cultivars (Andjus 1996; Moritz 2006). Thrips feeding on the ovaries of immature wheat heads results in kernel distortion and abortion. This has considerable consequences on yield as well as on the baking quality of flour (Kucharzyk 1998).

This observation led us to assess the potential for wheat midge to adapt to resistant wheat carrying *Sm1* by evaluating and comparing population of ear insects (wheat thrips and midges) on different cultivars. In order to explore the apparent differences in varietal characteristics leading to differential susceptibility to midge's infestation, a field experiment was conducted at Silstedt using twelve cultivars with different characteristics in terms of susceptibility and resistance. The objective was to categorize wheat varieties (susceptible and resistant) based on wheat thrips and midge populations.

Materials and methods

Winter wheat field

Twelve winter wheat cultivars were sown in sandy loam soil in RAGT 2n, Silstedt in central Germany (N 51.85°; E 10.85°) in October of 2008 and 2009. Five of these twelve cultivars (Glasgow, Welford, Robigus and Brompton) have proven resistance to *S. mosellana* (Ellis et al. 2009) as well as Skalmeje (Schliephake 2009, Personal communication). The experimental area was divided into plots. Two plots (replicates) were designated for each cultivar in a Completely Randomized Design.

Ear insect's evaluation

Numbers of thrips species *L. denticornis, L. cerealium,* and *T. angusticeps,* and wheat midges larvae (*S. mosellana* and *C. tritici*) were assessed by randomly collecting 10 ears per plot per cultivar, during June from two growth stages (GS 65 and 73) (Tottman 1987) in 2008 and 2009. These samples were frozen at –20°C. The thrips and midges were counted in the laboratory after finishing field work. The ears were dissected under a low power microscope. Each wheat ear was divided into 3 parts (low, middle and upper). The numbers of spikelets and of thrips and midge's larvae present on each as well as number of infested grains per ear were separately recorded for each part.

Kernel damage (shriveled, cracked, deformed kernels) in ears was also recorded. The relationship between numbers of thrips and midge larvae per ear was correlated with infested kernels in both years and among cultivars using Correlation Coefficient Statistics 9 (Thomas and Maurice 2008).

Statistical analyses

We assumed there was not a normal distribution of the pest count data within wheat ears. Figure 1 shows the distribution of the observed data for larval counts. In the present investigation we used a negative binomial distribution. The decision for this distribution compared with the frequently used Poisson distribution for counting data is based on a model selection with the use of the analytic criteria, AICC (Hurvich and Tsai 1989).

Accordingly we used a generalized linear model. Thus, the observed number of the i-th cultivar at date j in the k-th ear part of the l-th ear y_{ijkl} is assumed to be the realization of a random variable $\underline{y}_{ijkl}$ for those, the following is valid:

$$P(\underline{y}_{ijkl} = y_{ijkl}) = f_{Negbin}(y_{ijkl}|\mu_{ijkl}, \alpha)$$
$$(i = 1, \ldots a; j = 1, \ldots, b; k = 1, \ldots c; l = 1, \ldots n)$$

We have multiple measurements within the same wheat ear; i.e. counts within different ear parts (low, middle and upper). Thus, the random effect of the ear is included in the model and we have to deal with generalized linear mixed models (GLMM). Between μ_{ijkl} and η_{ijkl} we use the link function $\log(\mu_{ijkl}) = \eta_{ijkl}$, where η_{ijkl} is the so named "linear predictor".

Furthermore, in the present case we assume for the linear predictor η_{ijkl} the following model:

$$\begin{aligned}\underline{\eta}_{ijkl} &= \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} \\ &\quad + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \underline{z}_{ijl} \\ &= \mu + \delta_{ijk} + \underline{z}_{ijl}\end{aligned}$$

The model contains all main effects of cultivar, date and ear part as well as their two-way and three-way interactions. All fixed effects are summarized in the effect δ_{ijk}, which describes the effect of the i-th cultivar and time j and ear part k. In addition, the random ear effect $\underline{z}_{ijl}$ is included. For this effect we assume normal distribution ($\underline{z}_{ijl} \sim N(0, \sigma^2_{z(j)})$). In the course of the model selection we found a better model fit in case of time dependent ear variance estimation $\hat{\sigma}^2_{z(j)}$. Therefore we used heterogeneous variances.

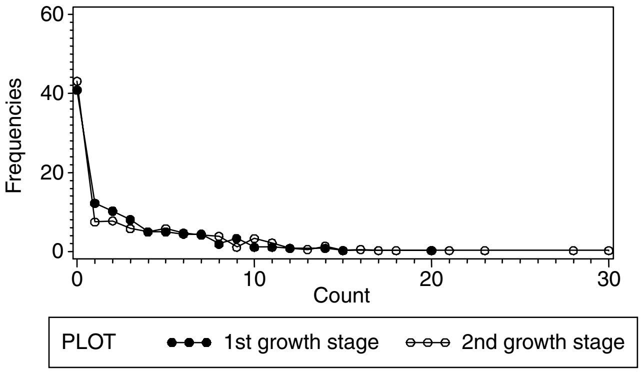


Fig. 1 Wheat midge larvae (observed data 2008, 1st and 2nd growth stages)

The parameters of the linear predictor $\underline{\eta}_{ijkl}$ and the variance components $\sigma^2_{z(j)}$ as well as their standard errors were estimated with the use of a conditional model and the maximum likelihood method with an adaptive Gauss-Hermite quadrature. The results presented in the next paragraph are on the original scale. Using the estimates of the linear predictor and the variance components we calculate

$$\hat{\mu}_{ijk} = \exp\left(\hat{\mu} + \hat{\delta}_{ijk} + \frac{\hat{\sigma}^2_{z(j)}}{2}\right) = \exp\left(\hat{\eta}_{ijk} + \frac{\hat{\sigma}^2_{z(j)}}{2}\right)$$

Derived from $\hat{\mu}_{ijk}$ we are able to make any accumulation of effects. For the estimate of the i-th cultivar it follows $\hat{\mu}_i = \frac{1}{b \cdot c}\sum_{j,k}\hat{\mu}_{ijk}$. The standard error of the estimates, for example $\hat{\mu}_i$, $\hat{\mu}_{i'}$ as well as their differences, was calculated by delta-method (Greene 2003, p. 913 ff.). Statistical analysis of the differences are based on the t-value = difference/standard error (difference) and thus on the t-distribution. The calculations described above were done using the SAS-Software version 9.2 (Proc GLIMMIX, Proc IML) (SAS Institute 2009).

Results

Three parts of wheat ear were examined for the presence of thrips and midges within two growth stages during two years. Detailed results of the differences between the parts are not reported here. Therefore, the following results are presented as mean value of ear part.

Ear insect evaluation

1. 1. 2008

A. Thrips [larvae and adults]

Significant differences were found (P = 0.011) in the number of total thrips per ear part among cultivars. Esket and Türkis cultivars had the highest numbers of thrips 5.7 and 6.2/ear part, respectively, while moderate values (2.5 & 2.6/ear part) were recorded in cultivars of Welford and Carenius. The lowest number of total thrips was found in Glasgow and Robigus cultivars (2.1 & 2.2/ear part), respectively (Fig. 2a).

There was a significant difference between Türkis and all cultivars except Esket (P = 0.91). There were significant differences between Esket and either Boomer (P = 0.038), Potenzial (P = 0.007), Tommi (P = 0.005), Global (P = 0.007), Carenius (P = 0.0008), Welford (P = 0.001), Skalmeje (P = 0.001), Brompton (P = 0.0003), Robigus (P = 0.001) or Glasgow (P = 0.001). Also, significant differences were

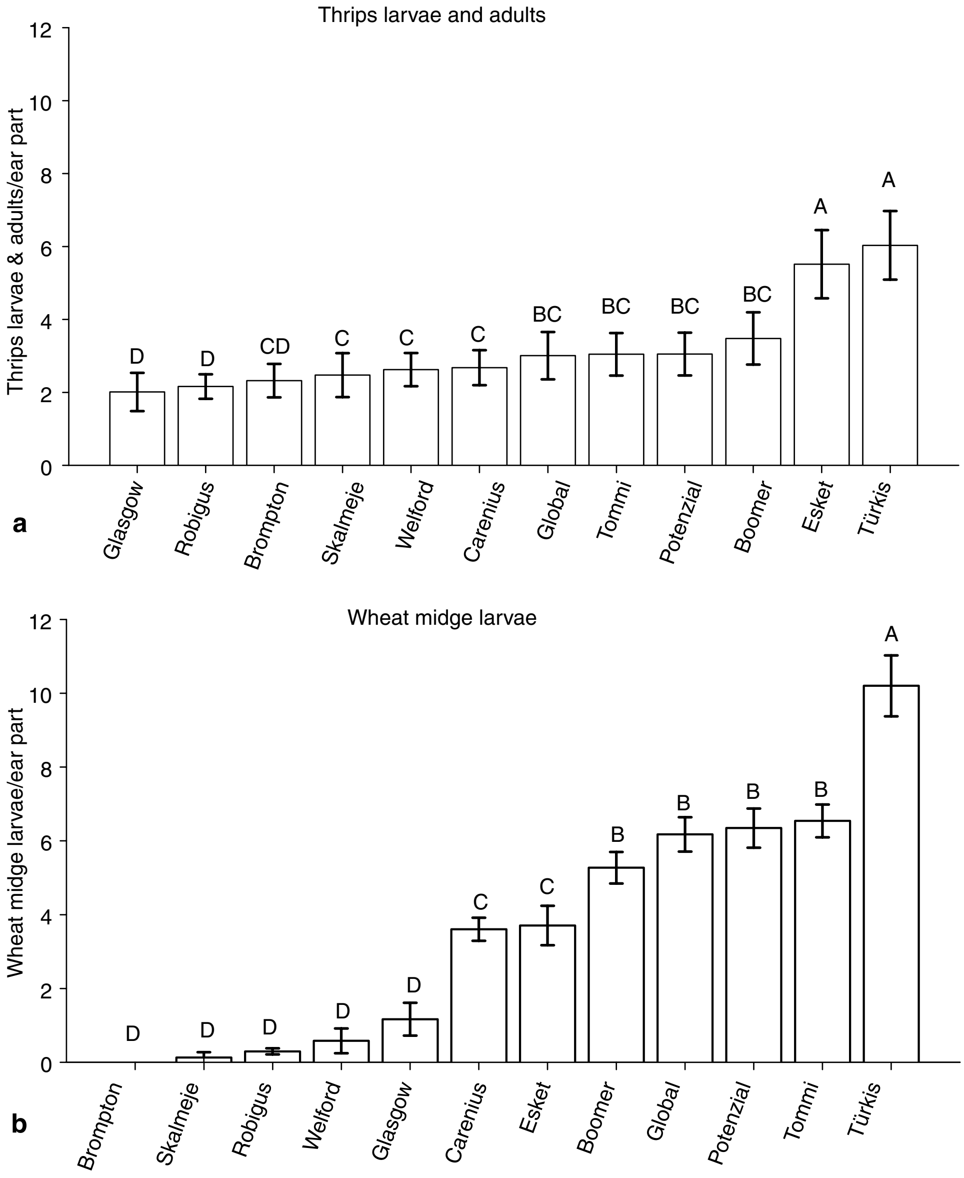


Fig. 2 Population of thrips larvae & adults (**a**) and wheat midge larvae (**b**) in different winter wheat (resistant & susceptible) cultivars in Silstedt 2008. Different letters indicate significant differences

found between Boomer and either Robigus (P=0.040) or Glasgow (P=0.044). Moreover significant differences were also recorded among Potenzial, Tommi, Global, Carenius, Welford & Skalmeje and Robigus or Glasgow as well (Fig. 2a).

B. Wheat midge's larvae

Significant differences (P=0.001) were also found between resistant and susceptible cultivars (Fig. 2b). There were significant differences (P=0.014) among susceptible cultivars, whereas the highest midge's larval population (10.2 larvae/ear part) has been found in Türkis as compared to other cultivars, while the moderate cultivars were reported in Carenius and Esket with value of 3.65/ear part. The least numbers of larvae were recorded in resistant cultivars namely Brompton, Skalmeje, Robigus, Welford and Glasgow (0.0, 0.1, 0.3, 0.6 and 1.2/ear part), respectively, there was no significant difference among resistant cultivars (Fig. 2b). There were four groups that have significantly different numbers of larvae. Most susceptible was Türkis. Tommi, Potenzial, Global and Boomer were less susceptible as Türkis, but with significantly higher larvae than Esket and Carenius, as well resistant cultivars, Glasgow, Welford, Robigus, Skalmeje and Brompton.

There was a significant difference between Türkis and all other cultivars without exception. Significant differences were recorded among Tommi and all cultivars except Boomer (P=0.051), Global (P=0.570), and Potenzial (P=0.777). There were significant differences among Potenzial and other cultivars except Boomer (P=0.115) and Global (P=0.810). Significant differences were obtained among Global and other cultivars except Boomer (P=0.153). Significant differences were recorded among Boomer and all cultivars except Global, Potenzial and Tommi. There were significant differences among Esket and all cultivars except Carenius (P=0.871). There were significant differences among Glasgow, Welford, Robigus, Skalmeje & Brompton and susceptible cultivars; while there was no significant difference within these resistant cultivars (Fig. 2b).

1. 2. 2009

A. Thrips [larvae and adults]

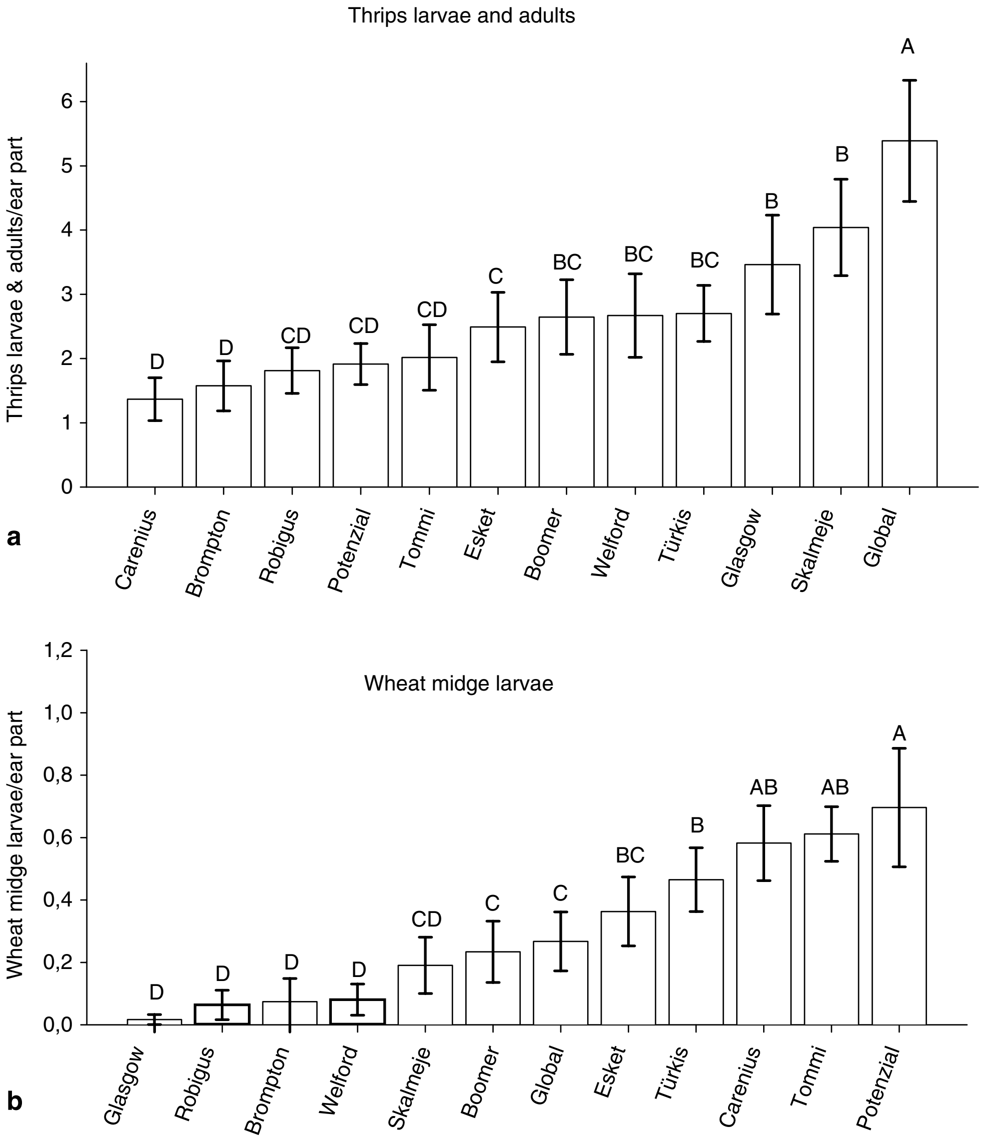
Significant differences were found (P=0.029) in the number of total thrips per ear part among cultivars. Global cultivar showed the highest numbers of thrips (5.6/ear part), while moderate numbers (2.4 and 2.7/ear part) were recorded in cultivars of Esket and Boomer. The lowest number of total thrips was found in Carenius and Brompton cultivars (1.3 and 1.6/ear part), respectively (Fig. 3a).

There were significant differences between Global and all cultivars as well as among Skalmeje and either Esket (P=0.001), Tommi (P=0.008), Potenzial (P=0.001), Robigus (P=0.001), Brompton (P=0.003) or Carenius (P=0.001) (Fig. 3a). Also, significant differences have been found among Glasgow, Esket (P=0.49), Tommi (P=0.048), Potenzial (P=0.022), Robigus (P=0.016), Brompton (P=0.006) and Carenius (P=0.001). Significant differences were also obtained among Türkis, Welford & Boomer and the following cultivars (Brompton and Carenius) and also between Esket and Carenius (P=0.003) (Fig. 3a).

B. Wheat midge's larvae

In 2009, the resistant cultivars (with exception of Skalmeje) were significantly separated from the other cultivars. Significant differences (P=0.009) were found between resistant and susceptible cultivars (Fig. 3b). There were significant

Fig. 3 Population of thrips larvae & adults (**a**) and wheat midge larvae (**b**) in different winter wheat (resistant & susceptible) cultivars in Silstedt in 2009. Different letters indicate significant differences



differences (P=0.034) among susceptible cultivars, whereas Potenzial showed the highest larval population (0.7 larvae/ear part) compared to other cultivars, while the moderate cultivars were Boomer and Global with values of 0.2 and 0.3/ear part, respectively. The least WBM values were recorded in resistant cultivars (Glasgow, Robigus, Brompton, Welford, and Skalmeje) ranged from 0.01 to 0.2/ear part (Fig. 3b).

Significant differences were found between: (i) Potenzial and other cultivars [except Carenius (P=0.758) and Tommi (P=0.769)]; (ii) Tommi or Carenius and all other cultivars [except Türkis and Esket]; (iii) Türkis and rest of the cultivars [except Carenius, Tommi and Esket], Esket and all other cultivars [except Global, Boomer and Skalmeje]; (iv) Global and Boomer and other cultivars except [Esket and Skalmeje] and Skalmeje, Welford, Brompton, Robigus and Glasgow and susceptible cultivars were found significantly different (Fig. 3b).

1.3. Pooled data of two years 2008 & 2009

A. Thrips [larvae and adults]

Generally, infestation of thrips was higher in 2008 compared to those in 2009. This may be due to the environmental conditions between the two years. There were significant differences (P=0.001) between the two years in the following cultivars (Carenius, Esket, Potenzial, Global and Türkis), while there was no significant difference (P=0.06) in cultivars of Boomer, Tommi, Brompton, Glasgow, Robigus, Skalmeje and Welford between both seasons. Significant differences were found (P=0.022) in the number of total thrips per ear part among cultivars. Türkis, Global and Esket cultivars had the highest numbers of thrips 4.5, 4.3 and 4.1/ear part, respectively, while moderate ones (2.6 and 2.8/ear part) were recorded in cultivars of Welford and Glasgow. The lowest number of total thrips was found in Carenius and Robigus cultivars (1.9 and 2.0/ear part), respectively (Fig. 4a).

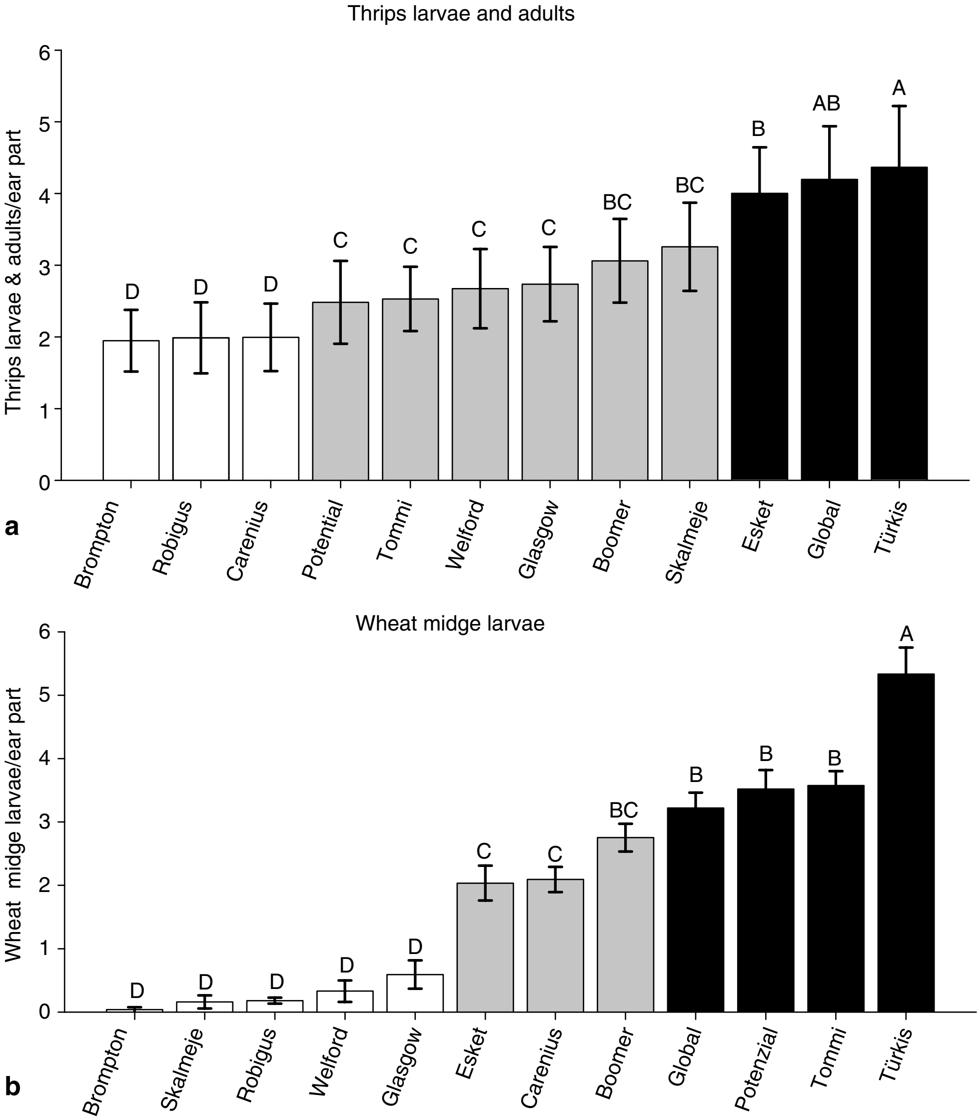


Fig. 4 Population of thrips larvae and adults (**a**) and wheat midge larvae (**b**) in different winter wheat (resistant & susceptible) cultivars in Silstedt in 2008 and 2009. Different colours indicate different infestation grades. Different letters indicate significant differences

There were significant differences between Türkis and all cultivars [except Global (P=0.999)]. Significant difference was obtained among Global and Glasgow (P=0.008), Welford (P=0.005), Tommi (P=0.001), Potenzial (P=0.005), Carenius (P=0.001), Robigus (P=0.001) and Brompton (P=0.001). Also, there were significant differences between Esket and each of Glasgow, Welford, Tommi, Potenzial, Carenius, Robigus and Brompton. Significant differences were recorded between Skalmeje & Boomer against Carenius (P=0.001), Robigus (P=0.012) and Brompton (P=0.002) and also among Glasgow, Welford, Tommi & Potenzial against Carenius, Robigus and Brompton (Fig. 4a).

B. Wheat midge's larvae

The proportion of ears infested with wheat midges also differed significantly (P=0.0025) between the two years. In general, wheat midge's infestation was lower in 2009 compared to those in 2008. There were significant differences (P=0.001) in both years among all cultivars except in the cultivars of Brompton, Skalmeje and Welford. Significant differences (P=0.006) were found among resistant and susceptible cultivars (Fig. 4b). There were significant differences (P=0.019) among susceptible cultivars, whereas Türkis had the highest midge's larvae population (5.3 larvae/ear part) compared to other cultivars, while the moderate cultivars were Esket and Carenius with value of 2.1/ear part. The least WBM values were recorded in resistant cultivars namely Brompton, Skalmeje, Robigus, Welford and Glasgow (0.1, 0.2, 0.2, 0.3 and 0.6/ear part), respectively, there was no significant difference among resistant cultivars (Fig. 4b).

There was a significant difference among Türkis and all cultivars. Significant differences were recorded among Tommi, Potenzial & Global and all cultivars except Boomer (P=0.051). Significant differences were evaluated between Boomer and all cultivars [except Carenius and Esket], also between Carenius and all cultivars [except Esket (P=0.862)]. Significant differences were found among resistant cultivars (Glasgow, Welford Robigus, Skalmeje and Brompton) and susceptible cultivars; while differences between resistant cultivars were not significant (Fig. 4b).

Table 1 Correlation coefficient between ear insects (thrips & wheat midges) and infested kernels in 2008 and 2009, significant differences are at 0.05 level

Studied years	Total thrips	Wheat midges
2008	+0.159	+0.99**
2009	+0.012	+0.99**
2008 & 2009	+0.085	+0.99**

The number of midge larvae per ear was significantly positively correlated (r=+0.99) with the percentage of infested ears. There was no significant correlation between total thrips and infested kernels (r=+0.085) (Table 1).

Ear insect's infestation grades (wheat cultivars groups)

The results indicated that winter wheat cultivars could be grouped into three categories based on thrips and wheat midges as shown in Fig. 4 in different colors among these groups in Table 2. The results indicated that the highest number of ear insects (thrips and midges) was found in cultivars of Türkis and Global, while the lowest values were recorded in Brompton and Robigus cultivars.

Discussion

Independent of the different levels of thrips and midge's larvae attack in both experimental years, Türkis, Tommi and Potenzial proved the most susceptible cultivars to WBM, while Brompton, Skalmeje, Robigus, Welford and Glasgow showed a clear resistance reaction in the two years. These results are similar with Volkmar et al. (2008, 2009); Gaafar et al. (2009); Gaafar et al. (2010) who studied some wheat cultivars in Germany for their susceptibility to thrips and WBM infestations.

Wheat midge populations were significantly positively correlated with the number of infested ears among culti-

Table 2 Infestation grades of wheat cultivars based on population of thrips and wheat midge larvae in 2008 and 2009. Different letters indicate significant differences

Grades	Total thrips/ear part		Grades	Wheat midge larvae/ear part	
	Cultivars	Mean		Cultivars	Mean
Low	Brompton	1.948 D	Low	Brompton	0.036 D
	Robigus	1.987 D		Skalmeje	0.159 D
	Carenius	1.994 D		Robigus	0.179 D
Moderate	Potential	2.483 C		Welford	0.329 D
	Tommi	2.530 C		Glasgow	0.590 D
	Welford	2.673 C	Moderate	Esket	2.034 C
	Glasgow	2.736 C		Carenius	2.093 C
	Boomer	3.062 BC		Boomer	2.751 BC
	Skalmeje	3.257 BC	High	Global	3.220 B
High	Esket	4.002 B		Potenzial	3.520 B
	Global	4.197 AB		Tommi	3.575 B
	Türkis	4.367 A		Türkis	5.332 A

vars in both years. These findings coincide with that concluded by Olfert et al. (1985) and Smith and Lamb (2001) who mentioned that such a strong correlation was expected because midges prefer to oviposit the eggs in wheat ears in the flowering stage, and when hatched, quickly move into the ear and damage kernels in the milky stage.

Variety trials showed consistently low wheat midge larval infestations on the resistant cultivars such as Brompton, Skalmeje, Robigus, Welford and Glasgow. In contrast, infestation levels on other cultivars varied between seasons such Boomer, Potenzial, Global and Tommi. Although cultivar such as Potenzial has *wm1* marker, but it is not resistant to orange wheat midges and its infestation vary from year to year. On the other hand, Skalmeje cultivar has also this *wm1* marker, and it is a resistant cultivar, therefore, midge's infestation was very low as confirmed by Schliephake (2009, personal communication). The low densities of wheat midge on resistant wheat in this study are consistent with those found in previous studies conducted with different objectives (Lamb et al. 2000a; Smith et al. 2004). Similar results were obtained by (Smith et al. 2007), pointing that wheat midge developing on resistant wheat was always very low compared with that of larvae developing on susceptible wheat cultivars and also they mentioned that small numbers of *S. mosellana* matured larvae in each wheat cultivar carrying the *Sm1* gene for antibiosis resistance against this insect. Synchronicity between the susceptible ear emergence stage of the crop and the peak of WBM flight activity was another key factor in determining larval infestation levels. The resistant cultivars had the lowest levels of WBM larval infestation as expected. This result confirms the importance of monitoring pest numbers in order to make the decision for insecticide treatment.

This may be due to that the ancestors in these cultivars evolved a defense which reduces or prevent eggs laying on spikes, based on some explanations: The most resistant wheat cultivars had a higher constitutive level and a more rapid induction of ferulic acid than susceptible cultivars, which increased the mortality of newly hatched larvae. Analysis of phenolic acids in grain samples showed that levels of ferulic acid were higher in infested grains of some cultivars compared to uninfested grains. Levels of *p*-coumaric acid were greater in the infested than in the uninfested samples of all the tested cultivars indicating that WBM damage is inducing production of this acid in the seed as reported by Ellis et al. (2009). This suggests that there might be another mechanism of WBM resistance (Smith et al. 2007).

Understanding the biochemical basis of resistance: although it is clear that the *Sm1* gene is responsible for resistance, as in Canada (Smith et al. 2007), the mechanism of resistance is still not understood. Canadian research suggested a correlation between increased levels of ferulic acid and resistance, but work with UK varieties does not support this. Further investigation is required to help future breeding programs (Ellis et al. 2009). Another demonstration by Ding et al. (2000) who mentioned that few wheat cultivars have a high level of antibiotic resistance to the larvae, which suppresses their growth and development; nearly all larvae develop successfully on susceptible wheat cultivars (Thomas et al. 2005).

There were less thrips or midges in the infested kernels of some cultivars than others in two years. Some wheat cultivars also have evolved a defense mechanism that deters oviposition by the wheat midge as mentioned by Berzonsky et al. (2002). These discrepancies might have been a result of speed ripening time as reported by Elliott et al. (2000). The wheat midge has evolved preferences for ovipositing at particular developmental stages of its host. This may have been sufficient to make some cultivars less favourable for oviposition (Lamb et al. 2001). Such cultivars are recommended to be cultivated in the next year.

In conclusion, to minimize the economic and ecological impact of *S. mosellana*, *C. tritici* and thrips, wheat producers in Germany should monitor ear insects, assess weather conditions and consider using resistant cultivars. Resistant wheat carrying the *Sm1* gene for antibiosis to wheat midge is highly effective in preventing the development of larvae. However, a small proportion of larvae are capable of maturation on resistant wheat and surviving to adult emergence, although at a lower rate than larvae did on susceptible wheat. Another possibility is that occasional larvae survive because of variability in the expression of the *Sm1* gene in wheat plants resulting from environmental influences as reported by Lamb et al. (2001). If a lower degree of infestation is predicted, producers may stick to their plans to grow wheat, but may choose a less susceptible wheat cultivar and early planting to avoid high midge populations during heading.

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References

Andjus L (1996) The research into the Thrips fauna and significance of the plants of spontaneous flora for the survival of pest species. Ph.D Thesis, Belgrade University

Berzonsky W, Shanower T, Lamb R, McKenzie R, Ding H (2002) Breeding wheat for resistance to insects. Plant Breed Rev 22:221–297

Doane JF, Olfert O (2008) Seasonal development of wheat midge, *Sitodiplosis mosellana,* in Saskatchewan, Canada. Crop Prot 27:951–958

Ding H, Lamb RJ, Ames N (2000) Inducible production of phenolic acids in wheat and antibiotic resistance to *Sitodiplosis mosellana.* J Chem Ecol 26:969–985

Elliott RH, Mann L, Olfert O (2000) Susceptibility of hard red spring wheats to damage by high populations of wheat midge. SRC-Saskatoon Res Lett 2000–2009, p 3

Ellis SA, Bruce TJA, Smart LE, Martin JL, Snape J, Self M (2009) Integrated management strategies for varieties tolerant and susceptible to wheat midge. HGCA Project Report number 451 May 2009, 148 pages

Gaafar N, Cöster H, Volkmar C (2009) Evaluation of ear infestation by Thrips and wheat blossom midges in winter wheat cultivars. In: F. Feldmann, D.V. Alford and C. Furk. (eds) Proc of 3rd Internat Symp on Plant Prot & plant health in Europe. Berlin, Germany, 14–16 May 2009, pp 349–359 (ISBN: 978-3-941261-05-1)

Gaafar N, El-Wakeil N, Volkmar C (2010) Assessment of wheat ear insects in winter wheat varieties in central Germany. J Pest Sci (Published online) doi: 10.1007/s10340-010-0325-2

Greene WHF (2003) Econometric analysis, 5th ed. Pearson Education, Upper Saddle River

Harris MO, Stuart JJ, Mohan M, Nair S, Lamb RJ, Rohfritsch O (2003) Grasses and gallmidges: plant defense and insect adaptation. Annu Rev Entomol 48:549–577

Hurvich CM, Tsai CL (1989) Regression and time series model selection in small samples. Biometrika 76:297–397

Kucharzyk H (1998) Thysanoptera and other insects collected in differently coloured traps in eastern Poland. Proc 6th Internat Symp on Thysanoptera, pp 81–87

Kurppa SLA (1989) Wheat blossom midges, *Sitodiplosis mosellana* (Géhin) and *Contarinia tritici* (Kirby) in Finland. During 1981–1987. Annu Agric Fenn 28:87–96

Lamb RJ, McKenzie RIH, Wise IL, Barker PS, Smith MAH, Olfert OO (2000a) Resistance to *Sitodiplosis mosellana* in spring wheat. Can Entomol 132:591–605

Lamb RJ, Tucker JR, Wise IL, Smith MAH (2000b) Trophic interaction between *Sitodiplosis mosellana* (Diptera) and spring wheat: implications for yield and seed quality. Can Entomol 132:607–625

Lamb RJ, Smith MAH, Wise IL, Clarke P, Clarke J (2001) Oviposition deterrence to *Sitodiplosis mosellana*: a source of resistance for durum wheat. Can Entomol 133:579–591

Lamb RJ, Sridhar P, Smith MAH, Wise IL (2003) Oviposition preference and offspring performance of a wheat midge *Sitodiplosis mosellana* on defended and less well defended wheat plants. Environ Entomol 32:414–420

McKenzie RIH, Lamb RJ, Aung T, Wise IL, Barker P, Olfert OO (2002) Inheritance of resistance to wheat midge, *Sitodiplosis mosellana,* in spring wheat. Plant Breed 121:383–388.

Moritz G (2006) Die Thripse. Die Neue Brehm-Bücherei Bd. 663, pp 384 (ISBN: 3 89432 891 6)

Oakley JN, Cumbleton PC, Corbett SJ, Saunders P, Green DI, Young JEB Rodgers R (1998) Prediction of orange wheat blossom midge activity and risk of damage. Crop Prot 17:145–149

Olfert OO, Mukerji MK, Doane JF (1985) Relationship between infestation levels and yield loss caused by wheat midge, *Sitodiplosis mosellana* (Diptera), in spring wheat in Saskatchewan. Can Entomol 117:593–598

Olfert O, Elliott RH, Hartley S (2009) Non-native insects in agriculture: strategies to manage the economic and environmental impact of wheat midge, *Sitodiplosis mosellana,* in Saskatchewan. Biol Invasions 11:127–133

SAS (2009) SAS Institute Inc., Cary, NC, 2009

Smith M, Lamb R (2001) Factors influencing oviposition by *Sitodiplosis mosellana* (Diptera) on wheat spikes. Can Entomol 133:533–548

Smith MAH, Lamb RJ, Wise IL, Olfert OO (2004) An interspersed refuge for *Sitodiplosis mosellana* to protect crop resistance and a biocontrol agent *Macroglenes penetrans* in wheat. Bull Entomol Res 94:179–188

Smith MAH, Wise IL, Lamb RJ (2007) Survival of *Sitodiplosis mosellana* (Diptera: Cecidomyiidae) on wheat with antibiosis resistance: implication for the evolution of virulence. Can Entomol 139:133–140

Thomas CR, Maurice SC (2008) Statistix 9, Ninth Edition, Managerial Economics McGraw-Hill/Irwin. (ISBN: 0073402818). More information at http://www.statistix.com

Thomas JB, Fineberg N, Penner GA, McCartney CA, Aung T, Wise IL, McCallum BD (2005) Chromosome location and markers of Sm1: a gene of wheat that conditions antibiotic resistance to orange wheat blossom midge. Mol Breed 15:183–192

Tottman DR (1987) The decimal code for the growth stages of cereals, with illustrations. Ann Appl Biol 110:441–454

USDA (2007) Annual world production summary, grains. http://www.usda.gov/. Accessed 4 Sept 2007

Volkmar C, Werner C, Matthes P (2008) On the occurrence and crop damage of wheat blossom midges (*Contarinia tritici* (Kby.) and *Sitodiplosis mosellana* (Geh.) in Saxony-Anhalt. Mitt Deutsch Gesell Allg und Angew Entomol 16:305–308

Volkmar C, Schröder A, Gaafar N, Cöster H, Spilke J (2009) Evaluierungsstudie zur Befallssituation von Thripsen in einem Winterweizensortiment. Mitt Deutsch Gesell Allg Angew Ent 17:227–230