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INHERITANCE OF RESISTANCE TO *Phomopsis* IN SUNFLOWER: STUDY OF LEAF AND STEM RESISTANCE AFTER ARTIFICIAL AND NATURAL INFECTION

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SUMMARY

Phomopsis helianthi Munt. Cvet. *et al.* has become one of the economically most important diseases of sunflower. To study the different resistance factors in leaf and stem, 29 inbred lines and 100 hybrids from a factorial cross of these lines were investigated. Observations across two environments with artificial leaf infection and in one environment with natural infection were conducted in 1998. Petiole score was taken as an indicator for leaf resistance after artificial infection. Diseased stems were used as a measure of stem resistance after natural infection. No correlation was found between resistance in the leaf and stem. Resistance against *Phomopsis* in both tissues was mainly controlled by additive gene action. Heterosis was not important. While stem resistance of hybrids seems to be predictable from their parents, a low correlation was found between line *per se* performance and general combining ability (GCA) effects for leaf resistance.

Key words: **combining ability, factorial crosses, *Helianthus annuus*, inheritance, *Phomopsis helianthi*, resistance**

INTRODUCTION

Stem canker caused by *Phomopsis helianthi* Munt. Cvet. *et al.* is one of the most widely distributed diseases of the cultivated sunflower. First identified in Yugoslavia in 1981 (Mihaljčević *et al.*, 1982), the pathogen is common now in most sunflower producing areas.

Ascospores infect lower or middle leaves usually after flowering. Small necrotic spots appear on leaf margins and spread along the main veins of the leaf. The fungus grows down the petiole to the stem, where the most characteristic and obvious symptoms occur. The fungus destroys the stem and causes drying and lodging

(Maširević and Gulya, 1992). Damages cause yield losses up to 40% (Demazure, 1995) and a reduced oil content (Franco and Morales, 1997) according to the stage of plant development at the time of infection.

Commercial hybrids with a high level of resistance to *Phomopsis* are available since Škorić (1985) obtained tolerant sunflower varieties from crosses between the cultivated sunflower and wild annual species. He found oligogenic resistance to *Phomopsis*, whereas Vrânceanu *et al.* (1994) stated that resistance was primarily controlled by partial dominance and additive genetic effects. Other authors (Tourvieille *et al.*, 1988; Vear *et al.*, 1997) confirmed the polygenic nature of resistance and its additive gene control. Sunflower breeders still need more information about the type of inheritance involved in *Phomopsis* resistance. Moreover, the correlation between line *per se* performance (LP) and general combining ability (GCA) is of major importance for optimizing selection methods in hybrid breeding.

Different types of resistance seem to be active in the plant tissues of leaf and stem (Tourvieille *et al.*, 1988). To investigate these different resistance factors, various artificial inoculation techniques using fungal mycelium on the leaf and petiole or ascospores on leaves (Bertrand and Tourvieille, 1987) as well as semi-natural infection tests (Vear *et al.*, 1997) have been developed. We determined the resistance of a range of sunflower genotypes by observing artificial leaf infection and natural infection. Our objectives were to (1) describe suitable *Phomopsis* resistance traits and infection tests, (2) study the inheritance of resistance to *Phomopsis* on 29 inbred lines and 100 hybrids from a factorial cross of these lines, and (3) estimate the genetic correlation between line *per se* performance and general combining ability (GCA) for several *Phomopsis* resistance traits.

MATERIALS AND METHODS

Sunflower genotypes

Four maintainer inbred lines of sunflower (*Helianthus annuus* L.), 25 restorer lines (Table 1) and 100 hybrids from a factorial cross between the corresponding CMS lines and the restorer lines were evaluated for reaction to *Phomopsis*. Detailed information about the inbred lines can be obtained from the corresponding author.

Field experiments

The 100 hybrids and the 25 restorer lines were evaluated for artificial infection in five 5 x 5 lattice designs with three replications. The four maintainer lines were evaluated in an adjacent randomized complete block design with six replications. The trials were conducted in 1998 at Eckartsweier and Biberach in Southwest Germany. The two environments for artificial leaf infection differed widely in the average temperature and precipitation during the growing season. In addition, all hybrids and parental lines were evaluated under natural *Phomopsis* infection in the

same year in a randomized complete block design with two replications in St. Martin le Beau (France). The latter environment is known for its intensive natural *Phomopsis* infection.

Table 1: Sunflower inbred lines used in a factorial cross to study resistance to *Phomopsis*

Line	Origin[1]	Line	Origin
Females (maintainers of CMS)			
BW93-009	1		
BW93-011	1		
HA-335	3		
NDBLOS	3		
Males (male fertility restorers)			
ARG-283	2	RW93-170	1
CM590	4	TUB-1705-328	2
CM591	4	TUB-1705-334	2
CM609	4	TUB-1705-33704	2
DES-1474-1	3	TUB-1705-33706	2
HIR34F	3	TUB-1705-338	2
MAX-287	2	TUB-346	3
PRA-RUN-417-1	3	TUB-365	3
RHA-857	3	TUB-5-3234	2
RW93-158	1	TUB-5-3235	2
RW93-165	1	TUB-5-326	2
RW93-167	1	XLAE-290	2
RW93-169	1		

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Fungal isolates

The *Phomopsis* isolate used for artificial infection originated from infected stems in France, kindly provided from CETIOM. Mycelium was cultivated at 25°C on a 1.5% agar medium containing 2% malt and 0.2% peptone extract.

Artificial infection

The leaf test described by Degener *et al.* (1998) to screen sunflower germplasm for *Sclerotinia* was used to determine resistance to leaf infection by *Phomopsis*. The tip of a leaf was infected with a *Phomopsis* mycelium explant and fixed by a self-adhesive label. The infested leaf was entirely covered with a transparent plastic bag containing water to prevent drying of the inoculum. Seven plants per plot were infected. The infection was considered to be successful when the lesion of the fungus reached the base of the petiole.

Data recording

We recorded following traits:

Leaf length: The length of the leaf measured in cm from the leaf apex to the base of the petiole. This trait was recorded immediately after infection.

Petiole score: The number of days from leaf infection until the lesion of the fungus reached the base of the petiole. Genotypes requiring more days for the fungus to reach the petiole were considered more tolerant.

Fungal growth: Fungal progression inside the leaf tissue was estimated from the ratio leaf length : petiole score.

Diseased stems: Percentage of stems with *Phomopsis* symptoms in each plot.

The latter trait was only measured after natural infection by *Phomopsis*.

Statistical analyses

Field data from individual plants of each plot were averaged to calculate plot means for each trait. Plants on which the inoculum was not successful in causing *Phomopsis* infection were excluded from the calculations. Randomized complete block and lattice analyses of variance were performed on the data of the inbreds and hybrids, respectively, for each environment. Entry means and adjusted entry means as well as the corresponding error mean squares and effective error mean squares were used to compute combined analyses of variance and covariance across environments. Estimates of variance components and phenotypic and genotypic correlations were obtained by standard procedures (Cochran and Cox, 1957; Mode and Robinson, 1959). Heritability (h^2) was calculated as the ratio of genotypic to phenotypic variances. Variances of general combining ability (GCA) and specific combining ability (SCA) were estimated according to established procedures (Hallauer and Miranda, 1981). The average values across the two environments of artificial infection and mean values under natural infection were used to estimate phenotypic correlations among resistance traits. Heterosis of hybrids were estimated by the following formula: mid-parent heterosis in %=100 (F_1-MP) / MP, where F_1= hybrid mean and MP= parental mean. All computations were performed with the computer package PLABSTAT (Utz, 1991).

RESULTS

The artificial infection rate varied from 89.4% at Eckartsweier to 96.8% at Biberach. The mean percentage for natural infection in St. Martin le Beau amounted to 51.1%. The female lines showed higher mean values for leaf length, fungal growth and diseased stems than the male lines (Table 2). Petiole score differed scarcely between male and female inbred lines. Generally, all traits showed slightly higher mean values for hybrids than for inbred lines. The hybrid NDBLOS x CM591 ranked first and BW93-009 x RW93-158 last for leaf length. The highest petiole score was scored for HA-335 x TUB-5-326 and the lowest for BW93-011 x MAX-287. The highest fungal growth was obtained for NDBLOS x ARG-283 and the low-

est for BW93-009 x CM591. However, NDBLOS x ARG-283 showed the lowest percentage of diseased stems after natural infection and BW93-009 x RW93-169 the highest percentage (data not shown). Mid-parent heterosis was small for all traits (Table 2).

Table 2: Means, range, estimates of various variance components, heritabilities (h^2) and mid-parent heterosis (MPH) for leaf length and two traits of resistance to *Phomopsis* after artificial infection in two environments and one trait of resistance to *Phomopsis* after natural infection in one environment

Statistic[1]	df[2]	Artificial infection			Natural infection
		Leaf length(cm)	Petiole score(days)	Fungal growth (mm/day)	Diseased stems(%)
			Inbred lines		
Mean females		18.4	22.8	8.3	46.6
Mean males		17.9	22.9	8.1	36.4
Overall mean		18.0	22.9	8.1	44.9
Range		13.9-22.1	14.7-36.5	4.5-12.5	0.0-100.0
σ^2_L	28	1.94**	3.71**	0.12	682.3**
σ^2_{LxE}	28	0.87**	4.86**	0.75**	-
σ^2	50	0.00	0.02	0.00	-
h^2		0.82	0.60	0.25	-
			Hybrids		
Mean		21.0	24.7	9.0	52.6
Range		15.2-25.8	15.8-38.4	4.7-14.3	0.0-100.0
σ^2_{GCA} females	3	1.61*	-0.14	0.35+	163.9*
σ^2_{GCA} males	24	0.69**	0.87**	-0.01	114.5**
σ^2_{SCA}	72	0.29*	0.30	0.08	44.9
σ^2_{GCAxE} females	3	0.14**	1.90**	0.11**	-
σ^2_{GCAxE} males	24	0.29**	0.53**	0.05	-
σ^2_{SCAxE}	72	-0.18	-0.02	0.05	-
h^2		0.60	0.47	0.18	-
MPH (%)		4.0	2.0	2.2	8.7

*, ** Significant at the 0.05 and 0.01 probability levels, respectively

[1] σ^2_L, σ^2_{LxE}, σ^2, σ^2_{GCA}, σ^2_{GCAxE}, σ^2_{SCA}, σ^2_{SCAxE} are variance components for lines, line x environment interactions, pooled error, GCA, GCA x environment interactions, SCA, and SCA x environment interactions, respectively

[2] Degrees of freedom

Genotypic variances for line *per se* performance (LP) were highly significant ($P \leq 0.01$) except for fungal growth (Table 2). Estimates of genotype x environment interaction variances were larger than the corresponding genotypic variance for petiole score and fungal growth. Variances for LP were two to six times larger than GCA variances. GCA variances were significant for most traits and greater for male than for female parents (Table 2). The variation between factorial crosses was mainly caused by GCA effects. The estimated GCA variances were two to four times greater than the SCA variances. Estimates of SCA variances were, except for leaf length, not significantly greater than zero. Variances of interactions of GCA effects

with environment were highly significant for most traits after artificial infection (Table 2).

Heritability (h^2) for resistance traits after artificial infection ranged from 0.25 to 0.82 for the inbred lines and from 0.18 to 0.60 for the factorial crosses (Table 2). The estimated h^2 was smallest for fungal growth, largest for leaf length, and intermediate for petiole score.

Table 3: Genotypic (above diagonal) and phenotypic (below diagonal) correlations among leaf length and two traits of resistance to *Phomopsis* in sunflower hybrids measured after artificial infection in two environments and one trait of resistance to *Phomopsis* measured after natural infection in one environment

Trait	Artificial infection		
	Leaf length (cm)	Petiole score (days)	Fungal growth (mm/day)
Artificial infection			
Leaf length (cm)		1.00^{++}	n.c.[1]
Petiole score (days)	0.55**		n.c.
Fungal growth (mm/day)	0.40	-0.36**	
Natural infection			
Diseased stems (%)	-0.50**	-0.03	-0.34**

*, ** Significant at the 0.05 and 0.01 probability levels, respectively
$^{+}$, $^{++}$ Exeeded once or twice its standard error, respectively
[1] not correlated: the genotypic variance of fungal growth was not significant

Phenotypic correlations were low between the two *Phomopsis* resistance traits after artificial infection (Table 3). Only the genotypic correlation between leaf length and petiole score was high. Diseased stems under natural infection were negatively correlated with leaf length as well as fungal growth under artificial infection.

Table 4: Phenotypic (r_p) and genotypic (r_g) correlations between line *per se* performance and general combining ability (GCA) for leaf length and two traits of resistance to *Phomopsis* measured after artificial infection in two environments and one trait of resistance to *Phomopsis* measured after natural infection in one environment

Trait	r_p	r_g
Artificial infection		
Leaf length (cm)	0.41*	0.40^{+}
Petiole score (days)	0.26	0.16
Fungal growth (mm/day)	0.29	n.c.[1]
Natural infection		
Diseased stems (%)	0.65**	-

*, ** Significant at the 0.05 and 0.01 probability levels, respectively
$^{+}$ Exceeded once its standard error
[1] not calculated: the genotypic variance of fungal growth was not significant

Significant correlations between LP and GCA existed only for leaf length, but not for petiole score and fungal growth after artificial infection (Table 4). Under natural infection, the correlation between diseased stems for LP and GCA was highly significant.

DISCUSSION

Phomopsis stem canker has steadily increased in sunflowers in recent years (Gulya *et al.*, 1997). In order to develop efficient resistance breeding programs, studies on the inheritance of *Phomopsis* resistance are necessary.

Scoring traits and infection tests for *Phomopsis* resistance breeding

Several resistance mechanisms seem to be involved in the different phases of the *Phomopsis* infection process (Tourvieille *et al.*, 1988). The progression rate of the pathogen through the leaves reflects leaf resistance, whereas another resistance factor seems to be located in the petiole-stem passage (Bertrand and Tourvieille, 1987). In our study, we investigated leaf resistance by determining petiole score and fungal growth after artificial infection. The latter trait was described by Vear *et al.* (1997) to be correlated with natural and semi-natural infection. In contrast with the results of these authors, we found no genotypic variation for fungal growth (Table 2), hence, it was not possible to investigate the inheritance for this resistance trait. Petiole score as a function of leaf length and fungal growth was primarily determined by leaf length (Table 3). However, because a typical infection starts at the leaf margins (Maširević and Gulya, 1992) and the growth rate of *Phomopsis* is fairly low, petiole score can at least be used to find highly susceptible inbred lines and, thus, can be useful in screening the most susceptible plants in testing of early generations in breeding. In a previous investigation (Degener *et al.*, 1999), the leaf test was also successful in screening for stem resistance by measuring the lesion length on the stem of artificially infected plants. In the present study, the fungal progression stagnated frequently inside the petiole tissue after passing the base of the petiole, presumably due to unfavorable weather conditions. Delos *et al.* (1995) reported that progression of the mycelium in the leaf can stop if the climatic conditions are unfavorable for development of the fungus. Therefore, in the present study stem resistance was measured with natural infection. Diseased stems describe the main resistance, because finally the lesion on the stem determines the yield losses (Bertrand and Tourvieille, 1987).

The fact that we did not find any correlation between petiole score and diseased stems (Table 3) proved that different resistance factors in the leaf and stem are involved. Similar results have been reported by Tourvieille *et al.* (1988), Dozet (1990) and Degener *et al.* (1999) after artificial infection of leaf and petiole. In agreement with Tourvieille *et al.* (1988) the different behavior of the hybrids with regard to both resistance traits demonstrates the partial and polygenic nature of resistance of sunflower to *Phomopsis*. The negative correlation between fungal growth and diseased stems was mainly attributable to the hybrid NDBLOS x ARG-283, which showed the lowest diseased stems combined with rapid fungal growth.

Selecting for *Phomopsis* resistance under natural infection in the field is recommended. Under conditions with less intensive infection, breeders are forced to use

artificial infection. In the case of a fungus like *Phomopsis*, where the pathogen grows relatively slowly through the tissue, we recommend to use a very aggressive isolate for artificial infection. Moreover, when scoring for stem resistance, breeders have to take into account leaf length. Under unfavorable climatic conditions, *Phomopsis* growth may stagnate inside of genotypes with longer leaves. This might be one explanation for the negative association between leaf length and diseased stems (Table 3).

Inheritance of resistance to *Phomopsis*

Variation among the factorial crosses was mainly caused by GCA effects for petiole score and diseased stems (Table 2). Thus, additive gene action seems to prevail for both traits. This was confirmed by the small amount of heterosis observed. Our results were in excellent agreement with those of Vear *et al.* (1997) who found GCA effects of much greater importance than SCA effects for leaf lesion length and stem infection score in a factorial of 10 inbred lines. Selection procedures that take advantage of additive gene action should thus be effective for development of hybrids with improved leaf and stem resistance to *Phomopsis*.

Miller *et al.* (1996) suggested that the GCA effects of female lines were relatively small when compared with the GCA effects of the male lines after screening 36 hybrids of factorial crosses for *Phomopsis* stem infection. Our results also indicate greater influences of male lines on hybrid leaf and stem resistance to *Phomopsis* than female lines (Table 2). However, in our study the four maintainer lines only showed moderate susceptibility to *Phomopsis*. Thus, we cannot make general statements about the GCA effects of female lines.

Relationship between inbred lines and testcross performance

Testing expenditures could be considerably reduced if the performance of the lines *per se* during early selfing generations could be used effectively for predicting their performance in hybrid combinations. The merit of using LP as an indirect criterion to improve GCA as compared to direct selection for GCA depends on the genotypic correlation between LP and GCA and on the relative size of the heritabilities of the two selection criteria (Falconer, 1989).

The moderate heritability for petiole score for both LP and GCA (Table 2) resulted from significant genotype-environment interactions, which are frequent in *Phomopsis* development (Gulya, 1998). In agreement with theoretical expectations (Wricke and Weber, 1986) we found a lower genotypic variance for testcross than LP performance for all traits and also a higher heritability.

The genotypic correlation between LP and GCA for petiole score was not significant (Table 4). The poor fungal progression in the leaf tissue after artificial infection allowed no inference about the prospects of selection for *Phomopsis* leaf resistance at LP without evaluation of testcrosses. It was not possible to clarify whether the same resistance factors are effective in lines and hybrids. Further artificial infection

tests are necessary to predict the behavior of hybrids for fungal growth with accuracy. The significant phenotypic correlation between LP and GCA for diseased stems (Table 4) suggest that for this trait the reaction of hybrids can be predicted from the trait values of their parents but additional tests in different environments are required to confirm these findings. Hence, up to now a simple testing of LP is not yet sufficient for any of the measured traits to improve GCA.

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HERENCIA DE LA RESISTENCIA A *Phomopsis* EN EL GIRASOL: ESTUDIO DE LA RESISTENCIA DE HOJA Y TALLO DESPUES DE LAS INFECCIÓNES ARTIFICIAL Y NATURAL

RESUMEN

Phomopsis helianthi Munt. Cvet. y otr. llego a ser una de las enfermrdades de girasol más importantes. Para estudiar diversos factores de resistencia de hoja y tallo, eran investigadas 29 líneas inbred y 100 híbridos creados por el cruce factorial de esas líneas. Durante el año 1998, las observaciones han sido hechas en dos localidades con la infección artificial y en una localidad con la infección natural. La reacción de peciolo fué tomada como indicador de resistencia de hoja a la infección artificial. Los tallos infectados eran utilizados como medida de resistencia de tallo a la infección natural. No fué constatada la conexion entre la resistencia de hoja y de tallo. La resistencia a *Phomopsis* en ambas especies de tejido era en general bajo el control de la acción aditiva de genes. La heterosis no tuvo importancia. Mientras, por un lado, parecia que la resistencia en los híbridos podia proveerse a base de sus padres, se encontro una baja correlación entre las performances de líneas *per se* y los efectos de la capacidad general de combinación (CGC) para la resistencia de hoja.

TRANSMISSION DE LA RESISTANCE AU *Phomopsis* CHEZ LE TOURNESOL: ANALYSE DE LA RESISTANCE DE LA FEUILLE ET DE LA TIGE APRES INFECTIONS NATURELLE ET ARTIFICIELLE

RÉSUMÉ

Le *Phomopsis helianthi* Munt. Cvet. *et al.* est devenu l'une des plus importantes maladies du tournesol au point de vue économique. Dans le but d'étudier différents facteurs de résistance dans la feuille et la tige, nous avons examiné 29 lignes inbred et 100 hybrides réalisés par le croisement factoriel de ces lignes. Au cours de l'année 1998, des observations ont été faites dans deux environnements où une infection avait été provoquée artificiellement et dans un environnement où l'infection était naturelle. La réaction du pétiole a servi d'indicateur de la résistance de la feuille à l'infection artificielle. Les tiges infectées ont été utilisées comme mesure de la résistance de la tige à l'infection naturelle. La relation entre la résistance de la feuille et celle de la tige n'a pas été établie. Dans les deux tissus, la résistance au *Phomopsis* était en général sous le contrôle de l'action des gènes additifs. L'hétérosis n'était pas important. Alors qu'il semblait qu'on pût prévoir la résistance chez les hybrides à cause des parents, on a trouvé une très mince corrélation entre la performance des lignes *per se* et l'effet des aptitudes combinatoires générales (GCA) dans la résistance des feuilles.