Characterization of *Fusarium* Root Rot Isolates from Sugar Beet by Growth and Virulence at Different Temperatures and Irrigation Regimes

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ABSTRACT

Harveson, R. M., and Rush, C. M. 1998. Characterization of *Fusarium* root rot isolates from sugar beet by growth and virulence at different temperatures and irrigation regimes. *Plant Dis.* 82:1039-1042.

Fusarium root rot, caused by *Fusarium oxysporum* f. sp. *betae* is one of several root diseases damaging to sugar beet production in Texas. As a primary symptom, most isolates produce a severe tip rot on the distal end of the taproot, in addition to discoloration of vascular elements and wilting. Tip rot distinguishes *Fusarium* root rot from another *F. oxysporum* f. sp. *betae*-incited disease, *Fusarium* yellows, which induces vascular discoloration and wilting but no root rot. This study was conducted to further characterize a selection of five Texas *F. oxysporum* f. sp. *betae* isolates representing different vegetative compatibility groupings, symptom types (tip rot, and non-tip rot), and hosts. Radial growth at six temperatures was measured for each isolate in culture on half-strength potato dextrose agar. Significant growth differences were detected, indicating a substantial amount of variation among the isolates. Virulence of isolates was evaluated by inoculating 6-week-old sugar beet plants with a microspore suspension and transplanting them into infested field soil. The plants were incubated at 20 and 30°C in controlled temperature boxes within the greenhouse and grown under two different irrigation schedules. After 6 weeks, plants were harvested and assigned a root disease rating, and root and foliar dry weights were determined. Disease ratings among isolates at 30°C resulted in three isolates (all tip rot isolates) being severe, one mild, and one intermediate. At 20°C, only one isolate caused appreciable root damage. Irrigation treatments had no effect on disease incidence or severity. Significant differences in colony diameter growth and virulence among isolates at the two temperatures provide further evidence of variation among Texas *F. oxysporum* f. sp. *betae* populations. Results also suggest that the tip rot phenotype may be induced by some genetic factor unique to tip rot isolates. Therefore, the form name *F. oxysporum* f. sp. *radicis-betae* is proposed for those isolates from Texas causing a tip rot.

Fusarium oxysporum Schlechtend.:Fr. emend. W.C. Snyder & H.N. Hans. f. sp. *betae* Stewart, the causal agent of *Fusarium* root rot, is a major contributor to sugar beet yield losses in Texas. *Fusarium* root rot is one of several root diseases occurring in Texas in a complex that includes *Rhizoctonia* root rot, *Aphanomyces* root rot, and rhizomania (11), but its basic etiology is poorly understood. *Fusarium* root rot from Texas often is characterized by a severe tip rot, in addition to the wilting and vascular discoloration that are normally associated with diseases incited by *F. oxysporum*. This tip rot symptom is common to the disease in Texas but has seldom been observed in other sugar beet-growing locations. Isolates from Oregon and California were tested in greenhouse trials utilizing field soil and were not able to cause the

tip rot symptom, whereas those from Texas consistently did so (19).

In a recent study (12), the sugar beet-growing regions of Texas were surveyed for *F. oxysporum* f. sp. *betae*, and isolates were analyzed for genetic variation by vegetative compatibility. It was found that isolates causing tip rot symptoms often formed heterokaryons in complementation tests with isolates not causing tip rot symptoms. This suggested that genes conferring vegetative compatibility are distinct from those associated with pathogenicity and that vegetative compatibility group (VCG) typing was incapable of distinguishing or identifying isolates causing the two major types of symptoms.

This same study also compared Texas isolates to those from a number of other sugar beet-growing states. It was determined that sugar beet isolates from the United States exhibited a substantial amount of variation based upon vegetative compatibility. No isolate from any one state was compatible with any other isolate from a different state (12). This confirmed results from previous studies using other techniques (random amplified polymorphic DNA, polymerase chain reaction, and

isozyme analysis) that isolates from Oregon, California, Montana, Colorado, and Wyoming were genetically distinct from those in Texas (8,19).

Although it has been demonstrated that *F. oxysporum* f. sp. *betae* isolates from Texas are genetically different from those from other states, it is still unclear as to the nature of the tip rot symptom. Therefore, this study was begun as a first step toward understanding the basis for the tip rot symptom type by characterizing a selected group of Texas isolates on the basis of their responses to different environmental conditions, including growth in culture at different temperatures and virulence at different soil temperatures and moisture levels. A preliminary report has been published (13).

MATERIALS AND METHODS

The five isolates used for this study were chosen based on a number of criteria. First, they represented examples of isolates previously used to establish the number of VCGs present among Texas isolates (12). This collection consisted of pathogenic isolates from both sugar beet and the closely related weed, red root pigweed (*Amaranthus retroflexus* L.). It also included isolates inducing both symptom types in addition to containing members of two distinct VCGs and one that was self-incompatible (Table 1).

Radial growth at different temperatures. Each isolate, started from a single spore, was grown on half-strength potato dextrose agar (PDA) and incubated in the dark at six temperatures, 10, 15, 20, 25, 30, and 35°C. There were six replications for each temperature-isolate combination. Colony diameter measurements were recorded daily for 8 days, and the study was repeated once. Data were analyzed by analysis of variance, and means were separated by Duncan's multiple range test. No differences were observed between the two tests, and no treatment-test interactions occurred, so experiments were combined to give a total of 12 replications per isolate per temperature.

Virulence evaluations at two soil temperatures and irrigation schedules. This portion of the study was conducted in 10-cm-diameter PVC tubes within the greenhouse. Each tube, 25 cm in length, was sealed at one end, filled with field soil, and placed in a controlled temperature box

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Accepted for publication 12 June 1998.

(10). Temperature was regulated in the rhizosphere by refrigerated air and a heating coil wound around the bottom of the box (10), and monitored by thermometers placed in the upper 10 cm of tubes.

Field soil was infested with approximately 1,000 conidia per gram for each isolate and stirred with a commercial cement mixer prior to being placed in the PVC tubes. A previous study under similar conditions found that colony-forming units of *F. solani* f. sp. *pisi* placed in the lower 10 cm of a 30-cm container failed to cause any noticeable root rot to peas (21). However, if inoculum was placed in the upper 10 cm or mixed throughout the profile, significant reductions were observed in plant dry weights and heights compared with uninoculated controls (21). To ensure disease development in the present study, 4- to 6-week-old sugar beet plants (hybrid cultivar Ranger) were additionally root-dipped with a conidial suspension of 1×10^6 conidia per ml before being transplanted (one plant per tube) into the containers filled with infested soil. All tubes were watered equally prior to the addition of the inoculated plants.

Six treatments (five isolates plus deionized water-inoculated control), replicated six times, were included in this study. Treatments were completely randomized within each of two temperature boxes, held constant at 30 and 20°C. Within each temperature box, plants inoculated with each isolate treatment were exposed to two irrigation regimes, one watered once weekly (low) and the other twice a week (high). This included 12 tubes per isolate, with six being wet and six being dry, for a total of 72 tubes (plants) for each temperature box. Irrigation was accomplished by a drip sys-

tem using one emitter per tube and watering the soil to saturation, approximately 1 liter after 5 to 10 min duration.

Data collection. After 6 weeks, plants were removed from the tubes and rinsed clean of adhering soil. A root disease rating of 0 to 4 was performed as previously described for Fusarium root rot (11). Briefly, the rating system was as follows: 0 = no disease, 1 = less than 25% of vascular elements necrotic or localized lesions on root, 2 = 26 to 50% vascular necrosis or less than 10% of taproot rotted, 3 = over 50% necrosis of vascular elements and 10 to 25% of taproot rotted, and 4 = more than 25% of taproot rotted (11). Tops (including crown and foliage) were removed and dried separately from roots in paper bags in a soil-drying oven at 55 to 60°C. After 2 to 3 days, root and top dry weights were recorded. This experiment was repeated once.

All data were subjected to the general linear model procedure. Treatment means were separated by Duncan's multiple range test, and variance between the two tests was analyzed for homogeneity. Correlation analysis was also used to determine the relationship between root disease rating and foliar and root dry weights.

RESULTS

Radial growth at different temperatures. Results of growth studies are presented in Table 2. There were significant differences between isolates and their abilities to grow in culture at different temperatures. F125 grew best at lower temperatures, and growth was greatly reduced as temperatures exceeded 25°C. It reached its maximum growth at 25°C, while the other four did so at 30°C (Table

2). Above 30°C, all isolates were inhibited, but not as dramatically as F125. This agrees with most reports that *F. oxysporum* has optimum growth temperatures in the range of 25 to 28°C. It is interesting to note that three of the four remaining isolates that grew better at higher temperatures were members of the same VCG, whereas F125 was in a separate one (Tables 1 and 2). The self-incompatible isolate (F5) had the greatest growth among isolates after 8 days at 35°C, but not at 30°C. (Table 2).

Virulence evaluations at two temperatures and irrigation schedules. Variance between replicated tests was homogenous, and no treatment-test interactions were observed. Additionally, no differences from the two irrigation treatments were observed for root rot severity on the inoculated sugar beets. Both high and low levels of water applied during the experiment resulted in equivalent levels of disease (data not shown). Therefore, all data from both tests were combined to include 24 replications per isolate for each of the two temperature box treatments. However, there were large differences between the two temperatures evaluated, with significantly higher disease ratings at 30°C than at 20°C (Tables 3 and 4). Although all isolates had previously been determined to be pathogenic at ambient greenhouse temperatures of 25 to 30°C, (12), only F5 caused significantly higher disease ratings at 20°C than the uninoculated control. At this temperature, the remaining four isolates were essentially non-pathogenic. Plant dry weights did not correlate well with disease rating for any of the isolates except F44 at 20°C. (Table 3).

At 30°C, three isolates (F5, F127, and F156) caused severe damage to beet roots (Table 4). These were originally tip rot isolates collected from the field, and all three reproduced this symptom on plants at this temperature in the greenhouse. F125 was a non-tip rot isolate and produced moderate disease levels but no tip rot symptom. F44, although belonging to the same VCG as F127 and F156, produced mild symptoms that were statistically non-significant from the control. Like F125, F44 was a non-tip rot isolate and produced only a slight discoloration of several of the vascular elements in roots, but no tip rot. At 30°C, there was a significant negative correlation between disease rating and dry weight (Table 4).

DISCUSSION

It is surprising that such radical differences were observed among *F. oxysporum* f. sp. *betae* isolates in terms of growth at different temperatures in culture (Table 2). Although all isolates were considered to be pathogenic under greenhouse conditions from previous evaluations (12), significant differences among isolates occurred at all six temperatures evaluated. However, these

Table 1. Isolates of *Fusarium oxysporum* f. sp. *betae* selected for growth and virulence evaluations at different temperatures

Isolate	Symptom ^x	Source ^y	VCG ^z
F5	TR	B	SI
F44	NTR	B	1
F125	NTR	PW	6
F127	TR	B	1
F156	TR	PW	1

^x TR = tip rot isolate, NTR = non-tip rot isolate.

^y B = sugar beet, PW = pigweed.

^z Vegetative compatibility group; SI = self-incompatible.

Table 2. Radial growth of *Fusarium oxysporum* f. sp. *betae* isolates (mm) in culture at different temperatures after 8 days

Isolate	Temperature (°C)					
	10	15	20	25	30	35
F5	3.3 bc ^z	8.6 b	34.9 a	49.9 a	51.9 b	35.0 a
F44	3.1 c	7.0 c	33.6 c	48.2 b	54.2 a	26.3 d
F125	8.1 a	12.0 a	34.2 b	44.0 d	40.7 d	15.1 e
F127	0.8 d	6.1 d	29.0 e	42.1 e	45.0 c	30.5 b
F156	3.7 b	6.9 c	32.5 d	46.2 c	52.7 b	29.1 c

^z Values represent the means of 12 replications for each isolate at each temperature. Means followed by the same letter are not significantly different according to Duncan's multiple range test ($P = 0.05$).

growth differences did not correspond to differences in virulence among the same isolates at 20 and 30°C.

Results of this experiment demonstrate that irrigation had no effect upon disease severity. This may possibly be explained by early infection soon after transplantation, since all tubes were watered equally at the initiation of the experiment. If the low-water treatment plants were already infected, perhaps the lack of any additional irrigation would not affect further disease development. Previous studies on soil moisture and its influence on *Fusarium* disease severity have produced contradictory results. Most studies conclude that *Fusarium* wilts are favored by wet soil, presumably because *Fusarium* disease progression depends upon movement of microconidia in the xylem after it enters the host (4,5). Conditions that slow transpiration, such as dry soil, are thought to also slow conidial transport up the stem (4). However, some earlier studies contradict these findings and report that severity of *Fusarium* wilt of tomato, cabbage, and spinach was higher following hot, dry weather, with little or no disease following cool, moist conditions (3,14,24). To our knowledge, this is the first report of a *Fusarium* disease not influenced by soil moisture.

Very little root damage occurred at 20°C, except for that produced by F5, but disease severity was much greater for all isolates at 30°C (Tables 3 and 4). This phenomenon of enhanced disease expression and severity at higher temperatures has been reported for *Fusarium* wilt of cabbage (2,24), tomato (3), and chrysanthemum (9). Although three isolates produced severe damage to plants at 30°C, it was unexpected that such substantial differences would exist in virulence among these isolates that were known to be pathogenic to sugar beet (Table 4).

It is interesting to note that the differences in virulence were not correlated with the different vegetative compatibility groupings or hosts from which isolates were collected. Pigweed (F125 and F156) and sugar beet isolates (F5, F44, and F127) both produced mild to moderate and severe symptoms at 30°C (Table 4). VCG 1 also was represented by both mild and severe symptom-inducing isolates (Tables 1 and 4). F125, representing VCG 6, grew better than the others in vitro at lower temperatures, but it was not pathogenic at 20°C and was only moderately virulent at 30°C. It should also be pointed out that the most severe isolate at both temperatures (F5) was self-incompatible and could not be placed in a VCG.

Correlation coefficients for root disease ratings and plant dry weights, except for that of F44, were nonsignificant at 20°C (Table 3). This shows that pathogenicity at this temperature was negligible for most isolates. Although F5 was pathogenic at

this temperature, as indicated by a disease rating of 2, there was little effect on plant growth. This phenomenon has been observed before in both field and greenhouse studies (10). Often, if conditions favoring plant growth predominate over those favoring pathogen development later in the season, a beet may recover by producing small feeder roots. This allows enough root growth to support a deceptively healthy foliage system, even though total root yield and taproot size are reduced (10). This same relationship is seen with isolate F127 in its nonsignificant disease correlation to foliar dry weight at 30°C (Table 4).

All isolates except F44 were collected from fields with long histories of sugar beet production. F44 was isolated from a field cropped to sugar beets for the first time. Its presence in this field could be explained by an introduction on sugar beet seed, since *F. oxysporum* f. sp. *betae* has been demonstrated to be seedborne (17). However, this is unlikely because it was not vegetatively compatible with any isolates from Oregon (12), the location where all U.S. sugar beet seed is increased. It is also possible that it was native to Texas soils, surviving on pigweed or some other weed (18). Windels and Kommedahl (27) similarly identified large populations of *F. oxysporum* from virgin prairie soils in Minnesota.

The most significant result from this study was that neither water nor temperature changed symptom phenotypes for the five isolates evaluated. The three tip rot isolates (F5, F127, and F156) produced the greatest amount of disease at 30°C and also reproduced the same root rot symptom in the temperature boxes that they demonstrated in the field. Only F5 induced a tip rot at 20°C. The non-tip rot isolates (F44 and F125) did not produce tip rot symptoms at either temperature. This suggests that these isolates are genetically distinct, causing different symptoms (diseases), and that symptom phenotype is not a result of different environmental conditions.

Examples of extreme genetic variation among *F. oxysporum* isolates have been well documented. Vegetative compatibility studies have included large numbers of VCGs (6,7,20), single-member VCGs (6,7), and self-incompatibility (12,15). All are representative of variation within *formae speciales*. Another study compared isolates of *F. oxysporum* f. sp. *tuberosi* that caused different symptoms on potatoes by vegetative compatibility. Although symptom type correlated with VCG for most isolates, several isolates causing a specific disease symptom were found to belong to more than one VCG (25). This is similar to the results of our study, because representatives of both symptom types from sugar

Table 3. Root disease ratings, root and top dry weights, and disease correlations with plant dry weights from sugar beet after inoculation with *Fusarium oxysporum* f. sp. *betae* isolates and incubated at 20°C for 6 weeks^v

Isolate	DR ^w	RDW ^x	(r) ^y	FDW ^z	(r)
F5	2.0 a	2.6 c	0.28	6.4 ab	-0.32
F44	0.2 b	3.3 bc	-0.67*	6.8 a	-0.55*
F125	0.3 b	3.5 bc	0.21	5.8 ab	0.03
F127	0.4 b	3.2 bc	-0.05	6.3 ab	-0.32
F156	0.4 b	4.0 ab	0.29	5.8 b	-0.11
Control	0.0 b	4.9 a	...	6.4 ab	...
Cumulative	...		-0.21		0.08

^v Values represent the mean of 24 replications for each isolate. Means in a column followed by the same letter are not significantly different according to Duncan's multiple range test ($P = 0.05$).

^w Root disease rating (0 to 4).

^x Root dry weight (g).

^y Correlation coefficient; * = significant ($P = 0.05$).

^z Foliar dry weight (g).

Table 4. Root disease ratings, root and top dry weights, and disease correlations with plant dry weights from sugar beet after inoculation with *Fusarium oxysporum* f. sp. *betae* isolates and incubated at 30°C for 6 weeks^v

Isolate	DR ^w	RDW ^x	(r) ^y	FDW ^z	(r)
F5	3.5 a	1.3 b	-0.72*	2.2 c	-0.79*
F44	0.7 c	5.1 a	-0.60*	8.8 a	-0.58*
F125	1.7 b	4.1 a	-0.90*	7.6 a	-0.70*
F127	2.4 b	2.0 b	-0.75*	4.8 b	-0.36
F156	3.3 a	1.5 b	-0.66*	4.4 b	-0.66*
Control	0.0 c	4.7 a	...	8.5 a	...
Cumulative			-0.78*		-0.74*

^v Values represent the mean of 24 replications for each isolate. Means in a column followed by the same letter are not significantly different according to Duncan's multiple range test ($P = 0.05$).

^w Root disease rating (0 to 4).

^x Root dry weight (g).

^y Correlation coefficient; * = significant ($P = 0.05$).

^z Foliar dry weight (g).

beet were found to belong to the same VCG (Table 1; 12)

The traditional sugar beet vascular wilt disease, *Fusarium* yellows, was first reported from Colorado (23); however, no mention of external root symptoms was made. No subsequent reports of this disease have included a description of root rot symptoms until the first report from Texas in 1989 (19). In Texas, root rot is still the primary symptom observed. The evidence obtained involving genetic and pathogenic characteristics of *F. oxysporum* f. sp. *betae* isolates from Texas and other sugar beet-producing states suggests that Texas root rot isolates are different and may warrant a distinct *forma specialis* to reflect this root rot symptom (19).

Snyder and Hansen's classification scheme designates *F. oxysporum* by the form name of the host (22). A number of studies have been conducted concerning several different root rot diseases caused by *F. oxysporum* where the form name has previously been used to designate the organism as a wilt pathogen on that host. In cases like this, Weimer suggested using a different form name to reflect the root rot symptom (26). Examples of this include *F. oxysporum* f. sp. *radicis-lupini*, causing a wilt and root rot of lupines (26), and *F. oxysporum* f. sp. *radicis-lycopersici*, causal agent of root and crown rot of tomato (16). However, several additional *Fusarium oxysporum* root rot diseases have also been reported without assigning a special *forma specialis* designation for the pathogen, including a root rot of Douglas fir seedlings and a wilt and root rot of spinach (1,14).

Previous studies have demonstrated substantial differences between *F. oxysporum* f. sp. *betae* isolates from the United States and those causing root rot in Texas (8,12,19). The results from this study have further shown that environmental conditions (temperature and moisture) do not change symptom phenotypes for Texas isolates. Therefore, we propose that the tip

rot isolates from Texas be designated *F. oxysporum* f. sp. *radicis-betae*, in accordance with previously suggested protocol (16,19,26), to represent *F. oxysporum* isolates causing root rot symptoms on sugar beet.

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