Occurrence and Transfer of a Biological Factor in Soil that Suppresses Take-all of Wheat in Eastern Washington

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ABSTRACT

A biological factor antagonistic to *Ophiobolus graminis* (=*Gaeumannomyces graminis*) occurs in eastern Washington fields of long-term dryland or irrigated wheat culture, but is absent from or present in ineffective amounts in noncultivated grassland and virgin soils. Severe take-all has been observed primarily in commercial fields of the Columbia Basin recently converted from their virgin state (native bunchgrass and sagebrush vegetation) to intensive wheat production with irrigation, but not in wheat fields with a long history of irrigated or dryland wheat. The fungus is prevalent in all soils, but apparently is suppressed in some by microbial antagonism.

The antagonistic properties of a soil were eliminated in the field and greenhouse by methyl bromide fumigation, and in the greenhouse by steam-air pasteurization at 60 C. As little as 1% addition of antagonistic soil to fumigated soil provided excellent restoration of antagonistic properties to the fumigated soil, and some restoration of antagonism in soil in field plots. In contrast, amendment of fumigated soil with virgin soil at 1 and 10% w/w provided little or no restoration of antagonism. This demonstrated the difference in antagonism between cropped and virgin soils, and the transmissibility of the factor in the greenhouse and the field. The nature of the antagonistic factor is discussed.

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Take-all of wheat caused by *Ophiobolus graminis* Sacc. [=*Gaeumannomyces graminis* (Sacc.) Arx & Olivier] in the Northwest, USA, east of the Cascade Mountains occurs almost exclusively in the irrigation districts of the Columbia Basin and southern Idaho (5). The disease has never been reported to occur in the semi-arid wheat-fallow areas of eastern Washington and north central Oregon, and is rarely observed (22) in the subhumid Palouse region of eastern Washington and adjacent Idaho. The distribution probably reflects the relatively high water potential requirements of the pathogen (6).

The absence of take-all in the dryland area cannot be due entirely to insufficient soil water for the pathogen according to observations at the Washington State University Dryland Research Unit, Lind, Washington. A 1.5 acre field plot on this station with a history of dryland wheat-fallow was experimentally amended with *O. graminis*-infested stubble in 1967, and cropped annually since then to sprinkler-irrigated wheat. After five consecutive crops, only limited take-all had developed. By contrast, two commercial fields of sprinkler-irrigated wheat 5 miles away from the Lind station showed severe take-all in 1967, one after 3 consecutive years of wheat cropping; the other after only two consecutive wheat crops. These two fields were recently reclaimed virgin areas, and had no history of dryland wheat. Surveys of other commercial fields in eastern Washington and in the Columbia Basin have revealed a similar pattern, namely, that fields with a history of dryland wheat-fallow converted to intensive wheat with irrigation, or those long cropped to irrigated wheat develop little or no take-all whereas those recently reclaimed from sagebrush/bunchgrass (7) and cropped 2 or 3 consecutive years to irrigated wheat develop severe take-all. Similar findings have been reported from The Netherlands (11) and France (15) on previously noncultivated areas.

Menzies (18), working with potato scab caused by *Streptomyces scabies*, in the Columbia Basin and Yakima Valley in eastern Washington, observed that virgin soils (those recently brought into cultivation) supported severe disease development whereas soils cultivated for many years supported only minimal disease. Burke (2) noted that in soils of this same area, *Fusarium solani* f. sp. *phaseoli* was active in some but failed to persist in others. In England (20), Switzerland (24), and The Netherlands (11) an antagonism thought to be responsible for take-all decline may develop with wheat or barley monoculture. Thus, we had reason to suspect that the soils with which we were working might, in their virgin state, contain little antagonism, but develop antagonism to *O. graminis* with long-term intensive cropping with wheat.

MATERIALS AND METHODS.—*Locations and sampling.*—A number of locations were chosen in the

arid (less than 20 cm average annual precipitation) Columbia Basin; semi-arid (20-35 cm precipitation) dryland, wheat-fallow area; and subhumid (35-50 cm annual precipitation) Palouse in the extreme east of the state. The selection of any given site was based on (i) the presence of a field with a long history of intensive wheat, and (ii) the availability of virgin or noncultivated soil nearby. Fields selected in the Columbia Basin had been cropped annually for up to 12 years with irrigated wheat. The nearby virgin areas supported sagebrush/bunchgrass vegetation. In the semi-arid region, fields were Ritzville silt loams and had been handled for decades in a wheat-summer fallow rotation; nearby virgin areas were sparsely covered by native grasses. The Palouse fields were very fine textured Palouse silt loams with supplemental sprinkle irrigation; noncultivated areas were permanent grass pasture or virgin grassland.

Soil was collected from each of three profiles at depths 0-5, 5-10, and 10-15 cm, approximately equivalent to the surface layers, the seed zone near the depth of rod-weeder cultivation, and subseed nontilled soil, respectively.

Bioassay for naturally occurring inoculum.—Replicates of soil were pooled, sieved through a 5-mm screen, dispensed into 6-inch plastic pots, and sown with 50 seeds of 'Nugaines' wheat. After 21 days growth in an incubator at 20 C with 12 hr daily illumination, roots of the seedlings were examined (16) under water against a white background for lesions caused by *O. graminis.*

Laboratory tests for antagonism.—Three methods were used to assess comparative antagonistic properties of the soils.

Method-1 was patterned after that of Lester & Shipton (16), and compared soils for their influence on survival and subsequent infectivity of introduced inoculum of *O. graminis.* Soils were amended with 15% w/w cornmeal-sand inoculum of the fungus. The mixture was incubated at 20 C for 28 days after which it was dispensed into 6-inch plastic pots and sown to wheat to assay for surviving inoculum. Roots of the seedlings were examined after 21 days as described above.

Method-2 tested soils for suppressive properties using sterile sand amended with Hoagland's solution as a background medium. Inoculum of *O. graminis* was mixed with test soils, incubated at 20 C for 0 or 28 days, then blended with 500 g nutrient-amended sterile sand in quart jars and sown to wheat. The inoculum in this case was milled, infested oat kernels and sand (1:9, v/v). Various ratios of soil:inoculum were used (1:1, 5:1, 25:1, and 1:10), but each was proportioned such that the final mixture tested for infectivity in the sand weighed 125 g.

Method-3 compared soils for their relative capacities to reinstate antagonism to *O. graminis* in fumigated soil. A Ritzville silt loam from Lind was fumigated with methyl bromide. Aliquots (1,500 g) were then amended with live test soils at rates of 10% or 1% w/w, infested with *O. graminis* (0.5, w/w) as ground, infested oat-kernel inoculum, placed in 6-inch plastic pots, and sown to wheat. Assays for seedling infection were made 21 days later.

Studies of heat-sensitivity of the antagonistic factors.—Soils were treated for 30 min with steam-air mixtures (1) adjusted to give pasteurization treatments of 50, 60, 80, 90, and 121 C. The treated soils were then assayed for antagonism using Method-3.

Transfer of the antagonistic property in the field.—Lind.—The experimental field at Lind cropped 5 consecutive years to wheat was selected as the test site. An area 6 × 24 m was fumigated with methyl bromide (0.5 kg/10 m^2). This area together with adjacent, nonfumigated check areas was used to establish three treatments: fumigated, nonfumigated (check), and fumigated recontaminated. The recontamination involved disking about 50 kg of nonfumigated soil (from an adjacent area) uniformly into a 3 × 6 m fumigated area to a depth of 12-15 cm, making the final rate of recontamination with untreated soil about 0.5% w/w. Each 3-m wide plot was then subdivided and half-sown with four rows of 1:1 w/w mixture of Nugaines winter wheat seed and oat-kernel inoculum of *O. graminis*, and the other half to four rows of the same mixture, but with dead inoculum (autoclaved oat-kernel inoculum). All treatments were replicated four times.

Incidence and severity of infection by *O. graminis* were recorded at 2.5 months after sowing [Growth Stage-2 (14)], and again in the spring at 8 months after sowing (Growth Stage-10). Counts were made of plant populations and yields of straw and grain were also determined.

Puyallup.—Today little wheat is grown in Washington west of the Cascades, but a closely related disease of turf caused by *O. graminis* var. *avenae* (12) is very important in that region. There has never been a satisfactory explanation for why *O. graminis* is severe in the Puyallup region where soils are acid (pH 5.0-5.5) although the annual rainfall of about 40 inches per year is favorable to the disease. Field plots were established at the Western Washington Research and Extension Center, Puyallup, to determine whether antagonism present in the more-alkaline eastern Washington soils could be established there. An area of long-term, exclusively horticultural crops, was fumigated with methyl bromide (0.5 kg/10 m^2) and then subdivided into plots 1.5 × 6 m each. These plots in four replications were amended, respectively, with (a) soil from a field near Quincy (arid), cropped 12 consecutive years to irrigated wheat and (b) soil from a virgin area near a; (c) soil from the experimental irrigated plot at Lind, and (d) soil from a virgin area near c; (e) soil from a field near Pullman cropped 22 consecutive years to wheat or barley, and (f) soil from a virgin area near e; and (g) nonfumigated check soil from a site adjacent to the plot. Sufficient soil was spread over the surface of the respective plots so that, upon rotovation to 12 cm, the recontamination rate was about 1% w/w. The entire area was then uniformly sown in the fall to Nugaines wheat and mixed 1:1 w/w in the drill-box with oat-kernel inoculum of *O. graminis.* Incidence

and severity of disease were determined at 3, 6, and 9 months after sowing which corresponded to Growth Stages-2, 4, and 9-10.

RESULTS.—*Bioassays for inoculum.*—Inoculum of *O. graminis* was detected in virtually all soil samples collected from the arid, semi-arid, and subhumid regions in both virgin and wheat field soils (Table 1).

Bioassays for antagonsim.— Contrary to the earlier success of Lester & Shipton (16), Method-1 did not distinguish consistently between the noncultivated and wheat monoculture soils. There was a great reduction in survival (infectivity) of the added inoculum in the soil regardless of whether the soil was from a virgin area or a long-term wheat field.

Method-2 was used to compare soil from the field near Quincy cropped 12 consecutive years to irrigated wheat with that of an adjacent virgin area; from the field near Pullman cropped 22 consecutive years to dryland wheat or barley with that of an adjacent grassland area; and from the experimental irrigated plot site at Lind with a virgin counterpart. Portions of the cultivated soil were autoclaved and included as a check for inoculum virulence. Each soil was blended with inoculum at ratios 25:1, 1:1, and 1:10 (w/w). This provided a test where the antagonism was proportionally high to pathogen inoculum (25:1) and vice versa (1:10). The entire trial was in duplicate, one-half of the soil-inoculum mixtures were prepared 28 days prior to the other half, and stored at 20 C. All mixtures were tested at the same time for infectivity.

As with Method-1, inoculum mixed with soil and incubated 28 days generally lost most of its infectivity, regardless of the soil with which it was mixed (Table 2). The inoculum also declined in virulence in autoclaved soil, if the inoculum soil ratio was 1:1 or 10:1. At the 1:25 ratio, inoculum survived 28 days incubation in autoclaved soil, but did not survive as well in virgin soils. In general, survival after 28 days was poorest of all in cultivated soils (Table 2).

Best results were obtained when soils and inoculum were mixed and tested immediately (0 time) for infectivity. At the 1:25 ratio, cultivated soils were highly suppressive to the fungus in contrast to corresponding virgin soils where disease severity almost equaled that in the autoclaved checks (Table 2). At ratios of 1:1 and 10:1 the inoculum presumably swamped the antagonists, and neither

TABLE 1. Natural occurrence of inoculum of *Ophiobolus graminis* in eastern Washington wheat fields and virgin areas

Soil sources		Plants infected per depth of soil sample (%)		
		Soil sampling depth[a]		
District	Field	0-5 cm	5-10 cm	10-15 cm
Semi-arid wheat-fallow region				
Connell	- wheat	7[b]	5	1
	virgin	28	22	3
Lind	- wheat	21	0	6
	virgin	1	3	1
	supplemental irrigated wheat	23	4	6
Harrington	- wheat	7	3	3
	virgin	3	9	15
Subhumid Palouse, wheat-fallow or annual crop				
Dusty	- wheat	3	7	1
	virgin	7	4	0
	supplemental irrigated wheat	11	7	1
Pullman	- wheat	7	7	3
	virgin	26	1	1
Arid, full irrigation, intensive wheat region				
Pasco	- wheat	34	20	20
	virgin	3	2	7
Quincy	- wheat	54	51	34
	virgin	7	8	8
Moses Lake	- wheat	17	21	18
	virgin	1	0	1

[a] Each sample consisted of three separate subsamples taken within 2 m of each other at one location in the field and bulked according to depth. Three such sampling locations (reps) were chosen per field.

[b] Each value is the average for three reps (pots), 50 seedlings per pot, read 21 days after sowing.

TABLE 2. Influence of inoculum levels and incubation of the inoculum-soil mixture on severity of take-all in virgin (or noncultivated) versus monocultured wheat field soils

Soil sources[a]		Incubation time (days)	% Diseased plants [inoculum:soil][b]					
			1:25		1:1		10:1	
District	Field		plants infected	black culms	plants infected	black culms	plants infected	black culms
Lind	- wheat	0	64	0	10	0	100	1
		28	8	0	10	0	1	0
	virgin	0	94	0	100	0	100	10
		28	16	0	0	0	0	0
	check[c]	0	100	33	100	97		
		28	85	0	3			
Quincy	- wheat	0	27	0	100	10	100	3
		28	20	0	2	0	0	0
	virgin	0	100	16	100	13	100	40
		28	43	0	60	0	3	0
	check	0	100	54	99	100		
		28	82	0	34	0		
Pullman	- wheat	0	58	0	94	0	100	12
		28	10	0	7	0	0	0
	noncultivated	0	96	0	100	0	100	0
	grassland	28	14	0	13	0	0	0
	check	0	99	67	100	83		
		28	86	0	0	0		

[a] Pullman field, 22 consecutive years dryland wheat or barley; Lind field, 4 consecutive years irrigated wheat following dryland wheat-fallow: Quincy, 12 consecutive years irrigated wheat.

[b] Oat-kernel inoculum of the pathogen was mixed in different ratios with the soil and incubated at 20 C for 0 or 28 days, then 125 g of the mixture was diluted with 500 g autoclaved sand and planted to wheat. Five reps, 25 plants per rep, read 21 days after sowing.

[c] Wheat-field and virgin soil mixed 1:1 and autoclaved 30 min at 121 C.

virgin nor cultivated soil proved suppressive.

Method-3 was also used to compare the soil pairs from Pullman, Quincy, and Lind. In addition, it was used to compare a virgin soil from Lind cropped four successive times to wheat in the greenhouse with soil from long-term dryland wheat field from Lind. Each soil was tested with live, ground oat-kernel inoculum of *O. graminis*, and dead inoculum added at the same rate to measure naturally occurring inoculum.

This method clearly distinguished between cropped and virgin soils (Table 3). Percentage plants and roots infected was about the same in all treatments, but subsequent disease progression as revealed by extensive black plate mycelium of *O. graminis* on the seedling internode and coleoptile (culm infection) was greatest in each case where virgin soil was used. In addition, seedlings in soil recontaminated with soils with a cropping history were as tall and vigorous in appearance as noninoculated (dead inoculum) checks, in contrast to seedlings exposed to virgin soil which were stunted, chlorotic, and near death at the time of sampling, 21 days after planting.

Influence of pasteurization on the antagonistic properties of soils.—The soil pairs from Quincy, Lind, and Pullman each were pasteurized at 50, 60, 70, 80, and 121 C for 30 min. Antagonism was eliminated at 60 C (Fig. 1).

Introduction of antagonism into fumigated plots in the field.—Fumigation eliminated the suppressive nature of the soil to *O. graminis* at the irrigated Lind plot site. Consequently, most wheat sown with inoculum in fumigated plots developed severe take-all and died in the fall about the time of tillering. In contrast, recontamination of the fumigated soil with a small amount (0.5%) of nontreated soil provided substantial restoration of antagonism; most plants were only moderately infected (Fig. 2), survived throughout the season, and yielded at least some grain. Plants in nonfumigated inoculated plots were only slightly to moderately infected. Counts in December (4 months after seeding) of plants/3 m of row for fumigated, fumigated-amended with 0.5% soil, and nonfumigated plots were 22.7, 47.7, and 60.2, respectively, averaged for the four inoculated replicates. Counts for the same treatments noninoculated were 78.5, 83.0, and 82.7 plants/3 m of row.

The field trial in Puyallup confirmed the transmissibility of antagonism in soil from locations of contrasting climatic and soil conditions. Soil from the Quincy and Pullman fields were most suppressive to *O. graminis* and that from Quincy virgin least suppressive (Table 4). However, by harvest, take-all had become severe in all plots and there was virtually no grain produced. Possibly, the dosage of inoculum was too massive relative to the antagonism introduced to provide for sustained plant protection.

TABLE 3. Introduction of factor(s) antagonistic to *Ophiobolus graminis* into fumigated Ritzville silt loam in greenhouse pots using whole soil amendments

Soil sources		Added inoculum	% Plants infected and with black culms			
			10% amendment[a]		1% amendment	
District	Field		Plants	Black culms	Plants	Black culms
Pullman	- wheat	live	100	5	100	4
		dead	6	0	1	0
	virgin	live	100	39	100	28
		dead	0	0	0	0
Quincy	- wheat	live	100	1	100	6
		dead	2	0	0	0
	virgin	live	100	13	100	7
		dead	2	0	0	0
Puyallup	- wheat (gh)[b]	live	100	13	98	5
		dead	19	0	4	0
	virgin	live	100	4	100	0
		dead	0	0	0	0
Lind	- wheat	live	100	1	98	2
	irrigated	dead	5	0	1	0
	wheat	live	100	6	100	4
	dryland	dead	0	0	1	0
	wheat (gh)[b]	live	100	0	98	0
		dead	0	0	1	0
	virgin	live	100	9	100	30
		dead	0	0	1	0
Nonamended check, not fumigated		live	100	4		
		dead	2	0		
Nonamended check, fumigated		live	100	62		
		dead	0	0		

[a] Fumigated (methyl bromide) soil amended at 1 or 10% w/w with virgin (or noncultivated) versus monocultured wheat field soils, and with 1% w/w oat-kernel inoculum of the pathogen. Based on five reps, 25 seedlings per rep.
[b] Virgin soil, experimentally infested with *O. graminis* and cropped four successive times in the greenhouse.

DISCUSSION.–The existence of a microbiotia antagonistic to *O. graminis* in long-term wheat field soils, but not in virgin or noncultivated soils may account at least partially for the distribution of severe take-all in the Pacific Northwest. The disease is a problem in newly reclaimed virgin soils of the arid and semi-arid portions of the region, when wheat is grown 2 or more consecutive years in the same field with heavy irrigation. In contrast, it is generally not a problem or occurs only in limited amounts in fields where wheat has been grown for a long time. The pathogen apparently occurs in virtually all wheat fields of Washington, and on native grasses in virgin areas, a fact also noted by Sprague (23), but does not cause severe disease unless the biotic as well as abiotic climate is favorable. This natural occurrence of antagonism in some soils is apparently a highly effective form of biological control of *O. graminis*.

The antagonism to *O. graminis* in eastern Washington is probably similar to that associated with take-all decline in England (20, 21, 22), The Netherlands (11), Switzerland (25), and many other wheat-growing areas of the world. In Kansas (9), take-all was reported years ago to disappear from fields cropped continuously to wheat. A unique

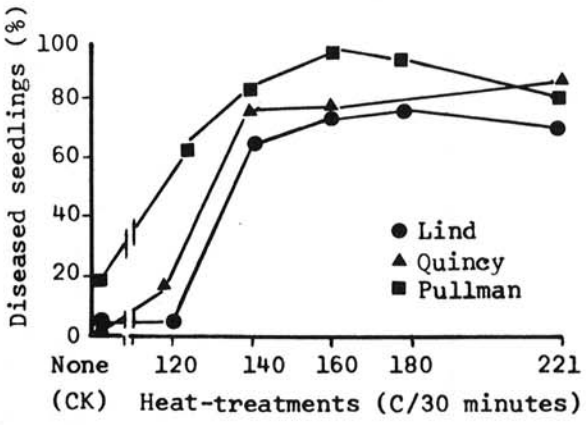

Fig. 1. Influence of heat treatment on antagonistic properties of three long-term wheat field soils to take-all caused by *Ophiobolus graminis* on wheat seedlings. Each nontreated or heat-treated standard soil sample was mixed 1% w/w with a standard fumigated (methyl bromide) soil (background bulk soil) to which 1% oat-kernel inoculum (w/w) of the pathogen had been added. Percentages are for plants with severe disease as evidenced by the presence of base-plate mycelium of the pathogen on the stem.

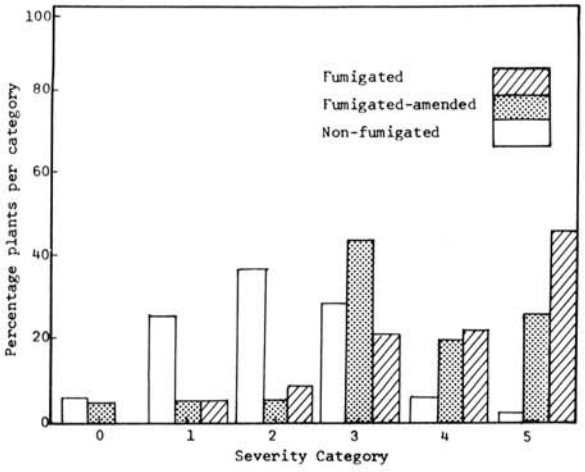

Fig. 2. Frequency distribution of take-all severity readings (0-5 score, 4 reps) on wheat 4 months after sowing in suppressive field soil in plots at Lind, Washington. Treatments were: fumigated, fumigated-recontaminated (ca. 0.5% w/w to depth 12-15 cm) with nonfumigated soil, and nonfumigated (control). *O. graminis* was introduced into each plot as infested oat-kernels sown 1:1 v/v in the seed furrow with the wheat seed. Checks used dead inoculum. 0 = healthy; 1 = lesions on less than 50% of seminal roots; 2 = more than 50% of seminal roots infected; 3 = infection on subcrown internode; 4 = infection on base of tiller; 5 = plant dead or nearly so.

observation in eastern Washington, however, is that soils of dryland areas apparently have developed a suppressive microbiota without evidence of interim severe take-all. Soils of the semi-arid wheat-fallow region are probably too dry for growth of *O. graminis* during much of the wheat-growing season (6), but probably are not too dry for many saprophytic organisms, particularly fungi and actinomycetes (13). During cultivation, dryland wheat-field soils undoubtedly acquire a microbiota that is more specific to wheat than exists naturally in virgin areas. The organisms selectively enriched from the native or introduced flora, because of their adaptation to the wheat plant and probably wheat roots, may ultimately hold potential as antagonists of *O. graminis* on wheat roots. Irrigation may subsequently satisfy the water potential requirement of *O. graminis*, but by then the microbiota developed during the previous years of dryland agriculture is adequate to buffer against the pathogen.

The sensitivity of the antagonistic microorganisms to 50-60 C pasteurization was also shown by Gerlagh (11) for the antagonism in soil of the Dutch polders. This provides circumstantial evidence that the antagonism is not due to actinomycetes or spore-forming bacteria; these groups generally survive 50-60 C temperatures by steam-air heat (1). Soil fungi and many nonspore-forming bacteria, on the other hand, are eliminated at 50-60 C and thus are prominent candidates for further study. Hyperparasites of *O. graminis* are known among the fungi (10, 17) and in The Netherlands, cellulose-decomposing fungi were implicated in the suppressive nature of some soils to *O. graminis* (19).

Menzies (18) demonstrated that one part scab-suppressive soil mixed with nine parts conducive soil would suppress scab just as well as the undiluted suppressive soil. Clark (4) similarly showed for virgin Columbia Basin soils of low nitrifying capacity that the addition of a small amount of cultivated soil increased the nitrifying capacity of the virgin soil out of proportion to the amount added. In our studies, 1% antagonistic soil added to fumigated soil provided full restoration of antagonism to the fumigated soil in the greenhouse, and some restoration in the field. Transfer of the factor in the field, although impractical as done, demonstrates in principle the feasibility of such a procedure. The possibility exists that a nonsusceptible crop can be used to increase antagonism to *O. graminis* (8) or, if known, the antagonists themselves might be introduced for successful biological control.

Irrigation and the concomitant lack of rotation was originally believed to be the main cause of increases in severe take-all in the Northwest USA (5), during the 1950's and 1960's. The disease became important almost exclusively in the irrigation districts (5), and had been observed in some nonirrigated areas only in seasons when rainfall was unusually high (23). A concern arose, therefore, as during the 1960's many wells were drilled and supplemental irrigation of the wheat became a common practice in the dryland wheat area. Cercosporella foot rot (*C. herpotrichoides*) has become more important in these supplementally irrigated fields, but so far take-all has not become important. The only exceptions known

TABLE 4. Introduction of factor(s) antagonistic to *Ophiobolus graminis* into fumigated soil in field plots at Puyallup using whole soil amendments

Soil sources		% Infection		Severity[a]		
District	Field	Dec.	March	Dec.	March	June
Fumigated check		81	93	3.1	3.4	4.0
Nonfumigated check		64	86	1.8	3.4	4.0
Fumigated, amended[b]						
Puyallup	- check	73	85	2.4	2.8	3.0
Quincy	- wheat	43	81	1.2	2.6	2.0
	virgin	74	96	2.3	4.3	3.5
Lind	- wheat	68	92	2.2	3.0	3.5
	virgin	71	89	2.6	3.9	3.2
Pullman	- wheat	59	88	1.8	3.0	2.0
	virgin	64	93	1.8	3.4	3.0

[a] Based on four reps, 25-35 plants per rep. For disease severity, plants were scored on a 0-5 basis; 0 = healthy, 5 = dead, 1, 2, 3, and 4 at correspondingly intermediate stages of disease severity. December and March data based on four reps, 25-35 plants per rep. June data based on over-all plot inspection on 0-5 basis, rather than individual plants.

[b] Test soils rototilled into fumigated (methyl bromide) plots to 15 cm depth at about 1% w/w of test to fumigated soil.

to us are the two fields near Lind in the dryland wheat region, which were actually newly reclaimed fields of virgin soil and thus were similar to virgin fields of the Columbia Basin farther west where the main take-all problem occurs. Based on this record and our own demonstration of an antagonistic or potentially antagonistic flora in soils long subjected to wheat culture, it appears growers of the traditional dryland wheat-fallow area can impose supplemental irrigation with little or no danger from take-all.

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