D. W. Burke and D. E. Miller
USDA-ARS, Irrigated Agriculture Research and Extension Center, Prosser, WA

Control of Fusarium Root Rot with

Fusarium root rot of beans (*Phaseolus vulgaris* L.), caused by *Fusarium solani* (Mart.) Appel & Wr. f. sp. *phaseoli* (Burk.) Snyd. & Hans., probably occurs to some degree in most bean fields throughout the world. The disease usually causes little damage if the plants are not stressed by other environmental factors that restrict root growth. The most obvious symptom is red to brown streaking or general necrosis of the taproot and hypocotyl cortex.

Fusarium root rot can be much more serious than the "foot rot" it is often considered to be. The most damaging effects are in the rotting that reduces the efficiency of the entire root system (3). The microbial ecology and behavior of the pathogen in the soil have been largely explained by W. C. Snyder and his students and co-workers through detailed studies at the University of California, Berkeley, during the past three decades (9). This article is based principally on research during the past two decades at the Irrigated Agriculture Research and Extension Center in Prosser, Washington, on the ecology and control of the disease through soil and water management and development of resistant beans.

Etiologic and Ecologic Premises

Beans planted in cold, *Fusarium*-infested soil or subjected to cool weather after emergence tend to have severe root rot, whereas those planted and raised in warm soil with adequate water tend to escape serious root rot. In cold soil, root growth is restricted and plants suffer physiological drought. Also, herbicides and decomposing organic matter may be toxicogenic in cold soil and aggravate the root rot problem (14).

Surface soil compaction by tractor wheels (Fig. 1) and subsurface tillage pans (7) are among the most noticeable root-restraining, disease-preconditioning problems involved in bean root rot. Hard subsurface soil layers caused by discs, rotary tillers, and other implements used during the past two decades to incorporate herbicides could well be responsible for the near static to declining average yields of beans in the United States, despite substantial concurrent genetic improvement of beans with regard to important disease resistance and other qualities.

The most frequently occurring predisposing stress is intermittent drought, especially in coarse-textured soils of low water-holding capacity and where soil compaction may confine the roots to a small volume (Fig. 2). In irrigated sandy loam soils infested with *F. solani* f. sp. *phaseoli*, variations in soil compaction and water distribution can cause up to 10-fold variations in seed yields within the same field. Drought during flower and pod development is especially serious, because it not only predisposes plants to severe root rot but also more directly restricts flower, pod, and seed development.

Another acutely aggravating contributor to Fusarium root rot is excess soil water, which, even for short periods during irrigations, reduces oxygen diffusion to roots and thus retards root growth. Temporary retardation of root growth leads to severe Fusarium root rot and permanently restricted plant growth (10) (Fig. 3). Such oxygen stress has been found to completely nullify the best known sources of resistance to the bean *Fusarium* and even to make bean roots susceptible to attack by the pea pathogen, *F. solani* f. sp. *pisi* (11). Bean plants in soil with no pathogenic *Fusarium*, even if the soil is infested with other pathogens such as *Pythium ultimum*, *Rhizoctonia solani*, and *Thielaviopsis basicola*, largely recover from brief periods of poor root aeration.

Good soil fertility is important for maximizing bean yields, whether or not root rot is a problem, but fertilization appears to have little if any effect on Fusarium root rot. Form and quantity of nitrogen have been reported to influence the disease in controlled experiments, but in the field, such influences are ephemeral and apparently unimportant, having little effect on disease severity.

Rotation of beans with such crops as small grains and alfalfa, which add large amounts of root and top residues to the soil, usually tends to counteract root rot by reducing soil compaction and increasing water-holding capacity of the soil. Decaying alfalfa roots provide channels for deep penetration of the soil by bean roots. If incorporated in the soil at least a month before planting, alternate crop residues may also reduce root rot through a salubrious effect on *Fusarium*-suppressive soil microflora. Sometimes, however, especially in cold, wet soil, recently incorporated, nondecomposed organic matter from almost any previous crop becomes toxic to bean plants and increases root rot (14). In *Fusarium*-

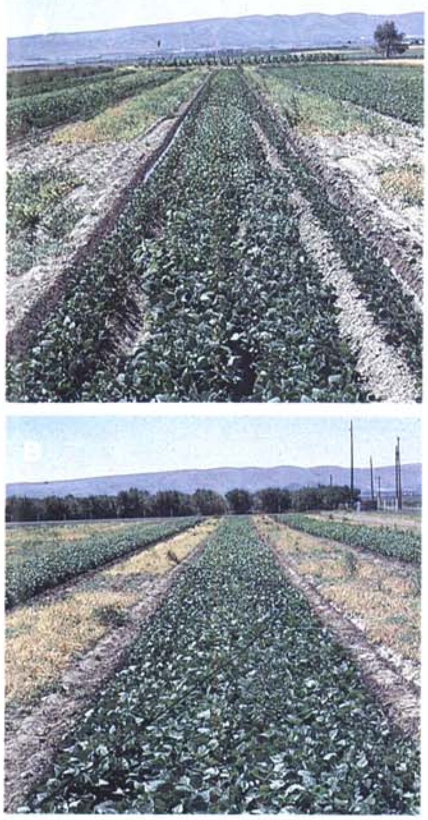

Fig. 1. Beans planted the same day with a four-wheel tractor that packed the soil in the outside rows. Fields were adjacent and infested by *Pythium ultimum, Rhizoctonia solani,* and *Thielaviopsis basicola*. Physical condition of the soil was considered nearly equal in the two fields; both had one compacted layer caused by plowing and another at the depth of preplanting herbicide incorporation. (A) Infested and (B) not infested with *Fusarium solani* f. sp. *phaseoli*.

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Resistant Beans and Cultural Management

infested fields, close spacing of plants tends to increase "foot rot" symptoms of the disease, but plant populations providing the most nearly complete ground cover produce the highest seed yields.

The supposed interaction of the seedling pathogens *Pythium*, *Rhizoctonia*, and *Thielaviopsis* in Fusarium root rot of beans has yet to be demonstrated except in greenhouse experiments, which seldom, if ever, correlate with field events in bean root rot. On the contrary, a recent 3-year field study (6) indicated that forms of *F. solani* attacking beans and peas were predominant and almost independent in causing significant root rots of these two crops in irrigated sandy loam soils, even where pathogens in the other three genera were obviously attacking the seedlings.

F. solani f. sp. *phaseoli*, unlike *Pythium* and *Rhizoctonia*, seldom causes serious damage to emerging bean seedlings. Usually, *Fusarium* colonizes the belowground parts of the seedling as they contact its germinable resting chlamydospores in the soil and remains an opportunistic pathogen throughout the life of the plant. *T. basicola* colonizes belowground parts of most bean plants and may cause considerable black cortical necrosis without seriously harming the plants. In some soils that are constantly wet, especially during the first half of the growing season, *Aphanomyces* or *Pythium* pathogens may predominate, or in soils high in previous-crop residues near the soil surface, *R. solani* may predominate, even though *F. solani* f. sp. *phaseoli* is present and infecting the roots.

Studies in Wisconsin soils seem to relegate large populations of pathogenic *F. solani* to minor roles in root rots of beans (12) and peas (5). In the usually moist soils of that state, *A. euteiches* may be the main yield-reducing pathogen in both beans and peas. *Fusarium* may become important only if drought occurs and if *Aphanomyces* has not already invaded the roots.

Direct Control Measures

Numerous efforts in direct control of Fusarium root rot have failed because treatments have been directed at reduction of localized "foot rot" symptoms on the hypocotyl and taproot. Rarely, if ever, have such treatments improved bean yields. In 1966 (3), we found that the effect of root rot on yields of beans in *Fusarium*-infested fields was not reduced even by complete protection of hypocotyls and taproots in "islands" of pathogen-free soil from which most of the root system extended into *Fusarium*-infested soil. Conversely, in another field where the root systems extended from *Fusarium*-infested islands into soil free from the pathogenic *Fusarium*, bean yields were equal to those of plants in the same field whose hypocotyls and taproots were not exposed to *Fusarium*. Vigorous, unrestricted roots outgrew and overcame local hypocotyl and taproot infections (Fig. 4).

Fusarium root rot of beans, like Aphanomyces root rot of peas (4), apparently affects most, if not all, of the root system when it significantly depresses yields. Control of such diseases by seed treatment or other localized treatments is impossible unless the treatments are capable of protective systemic or surface movement to the root systems. Nevertheless, localized treatments that control seed rot and seedling damping-off help ensure optimal plant populations, which in turn may help counteract yield depressions by root rot.

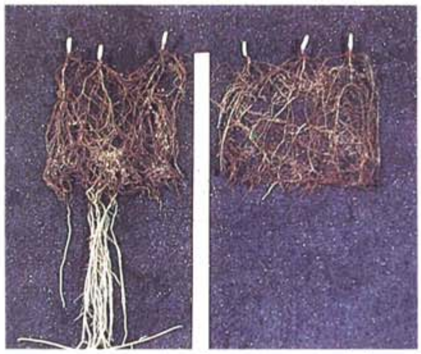

Fig. 2. Effect of soil water potential and infestation by *Fusarium solani* f. sp. *phaseoli* on growth of bean roots through compact soil. Soil was held at (left) −200 mb matric potential (sufficient water) and (right) −800 mb matric potential (moderate water stress). Marker indicates location of soil layer with bulk density of 1.55 g/cm^3; distance between marks is 4 cm. (From Miller and Burke. 1974. Phytopathology 64:526-529.)

Fig. 3. Beans in *Fusarium*-infested sandy loam soil saturated with water, as in an earlier irrigation. Soil saturation restricts oxygen diffusion to roots, retarding their growth and predisposing them to Fusarium rot.

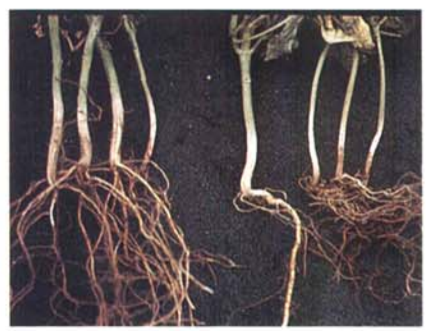

Fig. 4. Bean plants grown in a noninfested field in "islands" of soil infested by *Fusarium solani* f. sp. *phaseoli*. (Left) Roots grew unrestricted; (right) roots were enclosed in a clay pot, but a vigorous one escaped through a hole in the bottom of the pot. (From Burke. 1968. Phytopathology 58:1575-1576.)

General soil fumigation with such chemicals as chloropicrin and methyl bromide will usually control Fusarium root rot.

Development of Resistant Beans

Thus far, complete genetic resistance or immunity to *F. solani* f. sp. *phaseoli* has not been discovered in *P. vulgaris*. Furthermore, available genotypes with highest levels of resistance, as measured by degree of hypocotyl and root necrosis (15), are late-maturing and have not been

Table 1. Seed yields of bean cultivars differing in root rot susceptibility in adjacent *Fusarium*-infested and noninfested fields[a]

Cultivar	Noninfested field (kg/ha)	*Fusarium*-infested field (kg/ha)	Yield reduction due to root rot (kg/ha)	(%)	Disease index[b]
Red Mexican UI-36	4,038	1,901	2,137	52	62
Columbia pinto	3,456	2,209	1,247	36	61
Red Mexican Bigbend	3,524	2,622	902	25	76
Pinto UI-114	3,684	2,889	795	21	49
Red Mexican OR-5[c]	3,459	2,905	554	16	28
Sutter Pink	3,087	2,884	183	5	43
LSD 5%	385 kg	312 kg			5

[a] Average data from 20 replications of plots consisting of four 56 cm × 10 m rows in each field. Fertility, irrigation, and tillage were about the same in each field.

[b] Arbitrary ratings of root and hypocotyl necrosis 7 weeks after plant emergence: 25 = slight, 50 = moderate, 75 = severe, and 100 = very severe. Data are means of root evaluations made in 20 1-m sections of rows of each cultivar in the *Fusarium*-infested field. Root necrosis was negligible in the noninfested field.

[c] A selection from the cross Red Mexican UI-35 × PI 203958 for resistance to *Fusarium solani* f. sp. *phaseoli*.

D. W. Burke

Dr. Burke is a research plant pathologist with the USDA-ARS in cooperation with Washington State University at the Irrigated Agriculture Research and Extension Center in Prosser, Washington. He received his B.S. and M.S. degrees in agronomy at the University of Wyoming and his Ph.D. degree in plant pathology at Washington State University. For over 30 years, he has engaged in research on the ecology and control of bean root rot and the breeding of disease-resistant beans. From 1972 to 1982 he was research leader of the USDA-ARS Vegetable Crops Production Research Unit and location leader at Prosser.

D. E. Miller

Dr. Miller is a research soil scientist with the USDA-ARS in cooperation with Washington State University at the Irrigated Agriculture Research Extension Center in Prosser, Washington. He received his B.S. degree in agronomy from Utah State University, his M.S. degree in agronomy from Colorado State University, and his Ph.D. degree in agronomy and soils (soil physics) at Washington State University. For the past 25 years, he has been engaged in research work related to the evaluation of the effect of various soil physical properties on plant growth and soil and water conservation. Since 1972 he has been research leader of the USDA-ARS Soil and Water Management Research Unit and is currently location leader at Prosser.

satisfactory parents. The transfer of these high levels of resistance to desired early-maturing short-vine and bush-type beans has not been reported.

In 1967 we discovered in field tests that the early-maturing short-vine California cultivar Sutter Pink has an effective *Fusarium* resistance as measured by both severity of root necrosis and seed yield under root rot stress (Table 1). The high-quality cultivars Idaho Pinto UI-114 and Black Turtle Soup were also found to be less sensitive than most cultivars to yield reduction by root rot. Resistance to *Pythium* species, *R. solani*, and seedcorn maggot (8) is found mainly in certain pink and black, as well as brown and yellow, beans. Beebe et al (1) and Boomstra et al (2) recently reported a number of additional sources of resistance to *F. solani* f. sp. *phaseoli* that remain to be thoroughly studied and utilized as parents. The senior author, in 1967, tested a wild bean selection sent by O. Norvell and identified as *P. grisius*. This bean appeared to be immune to *Fusarium* in greenhouse tests. Norvell (*personal communication*) indicated that the bean was compatible in crosses with *P. vulgaris*, but, unfortunately, the seed source was lost and tests were never completed.

Recently, D. J. Hagedorn and R. E. Rand of the University of Wisconsin, Madison, released four snap bean breeding lines, Wisc. (RRR) 77, 83, 46, and 36, resistant to *Fusarium*, *Pythium* species, *Rhizoctonia*, and *Aphanomyces*. In 1983, M. H. Dickson of New York State University, Geneva, released three snap bean breeding lines, GRR 1869, 1819, and 1913, tolerant of *Pythium* and *Fusarium*, and J. J. Kolar of the University of Idaho, Moscow, released the great northern cultivar UI-60, productive under Fusarium root rot stress.

During the past 20 years, our project has cooperated in development of 12 cultivars, including pink, Red Mexican, and pinto beans, with economically effective levels of *Fusarium* resistance. All but one of these beans include in their parentage PI 203958, the first recognized source of substantial *Fusarium* resistance, which originated with O. Norvell (15). All but three of the 12 cultivars also have Sutter Pink as a parent. Those consistently performing best under root rot stress are more like Sutter Pink than like the late-maturing viny PI 203958. Unexpectedly, one of the new early-maturing short-vine cultivars with the most field resistance to root rot is Pinto NW-410, a selection from a single cross between Sutter Pink and Pinto UI-114. Table 2 compares seed yields of some new *Fusarium*-resistant cultivars with yields of older, susceptible cultivars when grown under different levels of stress in *Fusarium*-infested fields. The economic yield value of the partial resistance to Fusarium root rot in the new cultivars is obviously significant.

Concurrently with the development of colored beans, we have utilized *Fusarium*-resistant pink, pinto, and Black Turtle derivatives to establish *Fusarium* resistance in white, great northern, navy, and other small white bean breeding lines.

In developing beans resistant to root rot, we select 2-week-old seedlings from among segregating populations inoculated with pure cultures of *F. solani* f. sp. *phaseoli* in greenhouse tests. These selections are transplanted and grown to maturity in the greenhouse to produce seeds for a field test. Frequently, selections for resistance to *Fusarium* cultures fail to show field resistance and vice versa. Because Fusarium root rot in the field is severe only under various stress conditions, greenhouse selections are tested in *Fusarium*-infested fields. They are planted early in the spring (for cold soil exposure) in compacted seedbeds and are subjected to repeated water stress between irrigations. Early-maturing short-plant types outyielding commercial cultivars under these stresses are tested further under favorable field conditions. Those producing highest yields of good-quality seeds under all conditions are retained as candidates for further evaluation.

With this kind of testing and selection, genotypes have been developed with not only *Fusarium* resistance but also cold and drought tolerance. For instance, the pink bean cultivar Roza and Pinto NW-410 have better vigor and yielding ability after exposure in early growth to cold soil and later to drought than most other beans with which they have been compared (Table 2). The pink bean cultivars Roza and Viva yield well under dryland conditions in Colorado (D. R. Wood, *personal communication*). Other cultivars selected in the same process, Rufus Red Mexican and the pintos NW-590, Pindak, and Holberg, are highly productive under a wide range of conditions. The combination of *Fusarium* resistance and environmental stress tolerance tends to make these beans less variable in performance than other cultivars.

Yields of five bean cultivars under high and low water stress during 6 years in *Fusarium*-infested fields are shown in Figure 5. Plots of root rot-sensitive Red Mexican UI-36 and Pinto UI-114 nearest the source of irrigation water yielded twice as much as those farthest from the source. Cultivars resistant to Fusarium root rot were proportionally less variable. We have found yield under stress to be the only satisfactory measure of *Fusarium*-resistance in the field. By this method, progress in development of root rot-resistant lines of preferred plant types is more rapid than with the largely futile method of selection on the basis of root disease ratings only.

Cultural Management

We investigated various cultural methods of counteracting bean root rot by reducing environmental stresses. The most effective methods thus far have been use of the previously mentioned rotations, planting in warm soil, maintaining optimum soil water, and loosening compacted soil in the last tillage before planting (7). Loosening the soil has been the most dependable method. Subsoiler chisels (Fig. 6A) ripped the soil to a depth of 45–50 cm, either near the planter path or halfway between rows spaced 55 cm apart, in alternate interrow spaces (Fig. 6B). Irrigation in furrows could be applied only in the interrow spaces, which were not chiseled. Subsoiling loosened

Table 2. Effects of field conditions on seed yields of bean cultivars differing in sensitivity to Fusarium root rot

	Yield (kg/ha)			
Cultivar	**Continuous beans with stress**[a]	**Continuous beans with little stress**[b]	**Beans-wheat rotation**[c]	**Means of all fields**
Red Mexican				
UI-36 (S)[d]	1,092	2,195	2,307	1,702 (17)[e]
NW-63 (R)	1,808	3,431	2,928	2,519 (17)
Pinto				
UI-114 (S)	1,598	3,335	2,316	2,265 (16)
NW-410 (R)	1,988	3,667	3,294	2,791 (16)
Pink				
Roza (R)	2,070	3,389	3,338	2,970 (16)
Best selection[f] (R)	2,390	3,802	3,916	3,360 (16)

[a] Water stress between irrigations and stresses caused by cold soil after planting, soil compaction, and heat during blossom and pod set; mean yields from three replicate 1/740-ha plots from each of 7 years' experiments.

[b] Less water and weather stress; mean yields from three replicate 1/740-ha plots from each of 3 years' experiments.

[c] Beans in 2-year rotation with wheat; data from each of 5–8 years' experiments.

[d] S = susceptible, R = measurable level of resistance to root and hypocotyl necrosis.

[e] Number of experiments represented by mean.

[f] Highest yielding selection in each yield trial and usually highest yielding among all beans tested under root rot stress each season.

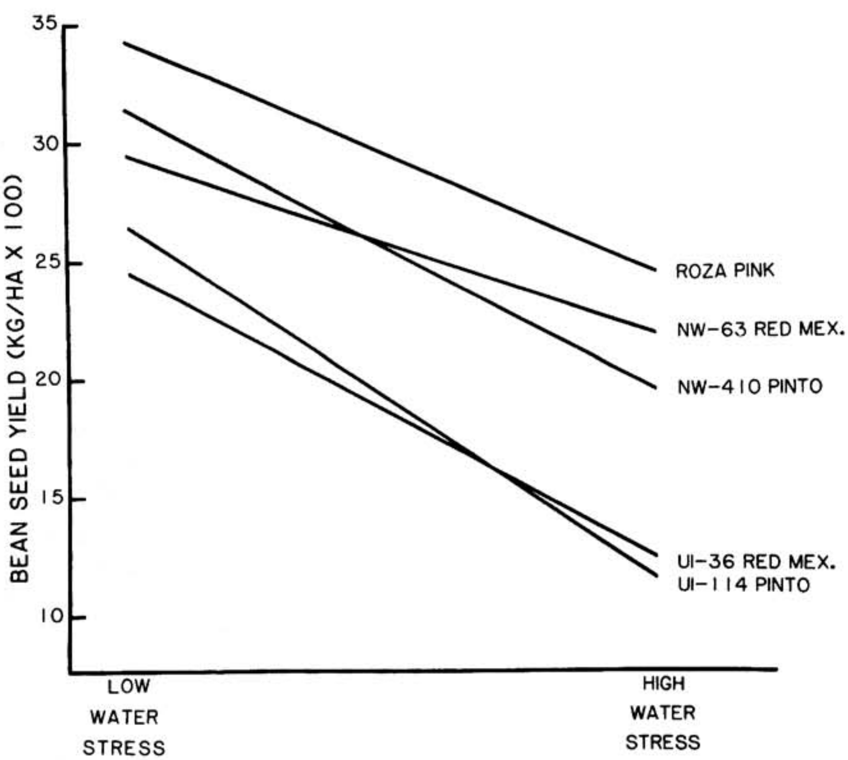

Fig. 5. Average bean seed yields from highest- and lowest-yielding plots of five cultivars grown in 12 experiments during 6 years in *Fusarium*-infested soil. Fields were irrigated in ditches between bean rows. Yields were highest at low water stress (nearest the water source) and lowest at high water stress (farthest from the water source).

compacted soil, including the plow sole, and permitted roots to extend down a meter or more. Roots in unchiseled plots were confined to the plowed layer or, in many instances, to the 10–12 cm underlaid by a "tillage pan" created by discs or other implements used to incorporate herbicides (Fig. 7A). Such treatments to loosen the soil largely counteracted the effects of Fusarium root rot on bean yields (7).

More recently, for practical purposes, smaller chisels attached to a tool bar on the planting tractor (Fig. 6C) have been used. These chisels, offset 2.5–3.5 cm from each planter path, rip the soil to a depth of 25–28 cm, thus breaking at least the compact layer created by herbicide incorporation. This tillage allows comparatively deep rooting (Fig. 7B), reduces water stress (Fig. 8), and thus, in conjunction with use of *Fusarium*-resistant cultivars, largely counteracts Fusarium root rot.

Ripping the soil has less effect on seed yields in noninfested than in *Fusarium*-infested fields (Fig. 9). Deep rooting promoted by ripping to loosen the soils should permit extension of irrigation intervals. With less frequent irrigations, incidence of Sclerotinia wilt can also be significantly reduced in areas with little summer rain.

Silbernagel (13) recently found that subsoiling to promote deeper rooting of bush-type snap beans largely controlled

Fig. 6. Subsoiler chisels (A) spaced 112 cm apart are adjusted (B) to rip the soil to a depth of 45-50 cm, centered between bean rows marked for subsequent planting. Ditch irrigation can be applied only in the unripped interrow spaces. (C) Smaller chisels attached to a tool bar on the planting tractor and offset 2.5-3.5 cm from the path of each planter rip the soil to a depth of 25-28 cm. Irrigation can be applied in all spaces between bean rows.

Fig. 7. Root development of bean plants in fields infested by *Fusarium solani* f. sp. *phaseoli*. Six weeks after planting, roots (A) are restricted to 10-12 cm of soil by compacted sole created by herbicide incorporation but (B) extend deeper where sole was ripped by small chisel. Roots (sprayed with paint) growing in (C) soil containing wheat crop residue and (D) loosened soil toward path of large subsoiler chisel. (E) Nearly mature plants growing in (left) compact soil and (right) soil ripped with large subsoiler chisel between rows at planting time.

Fig. 8. Bean plants in *Fusarium*-infested fields where soil was ripped to a depth of 25–28 cm near each row at planting time. (A) Seven-week-old plants before first postplant irrigation. In center four rows, dark green (water-stressed) plants growing in nonripped soil alternate with light green (nonstressed) plants growing in ripped soil. (B) Nearly mature plants show (left) benefits of soil ripping and (right) stunting effects of wheel and subsurface soil compaction.

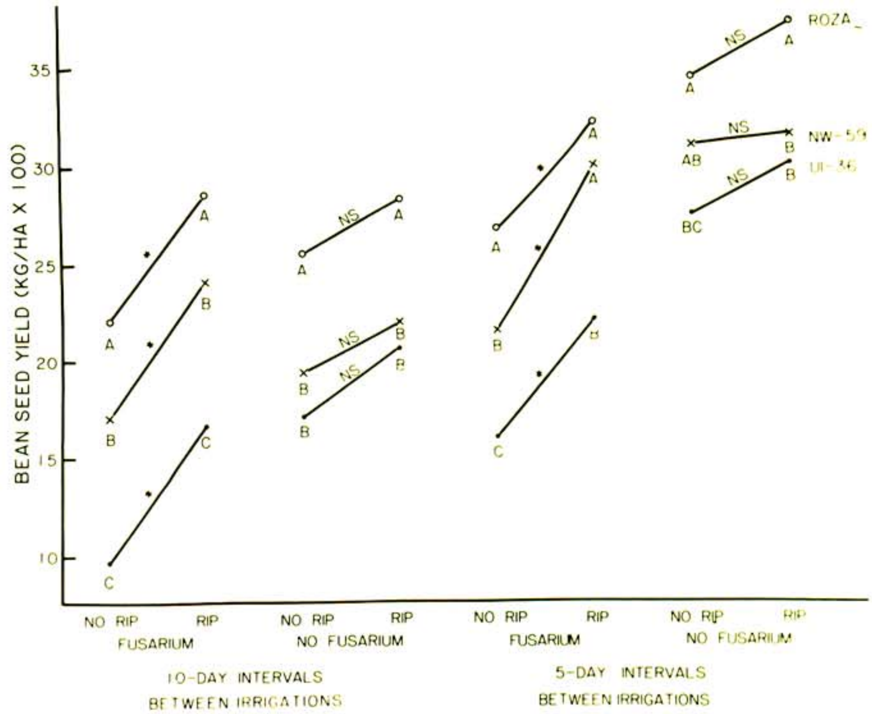

Fig. 9. Effects of ripping the soil to a depth of 25–28 cm near each bean row at planting time on yields of three bean cultivars (Roza pink and Red Mexican NW-59 considered resistant and Red Mexican UI-36, highly susceptible) grown in adjacent fields of sandy loam soil, one infested by *Fusarium solani* f. sp. *phaseoli* and the other not infested. Beginning 6 weeks after planting, sprinkler irrigations were applied at 5-day (near optimum) and 10-day (drought-inducing) intervals. Each data point is the mean of four replicate 1/740-ha plots. Asterisks indicate significance at the 5% level for effects of ripping the soil. Data points perpendicular to each other and subtended by the same letter are not significantly different.

Fusarium root rot in sandy loam soil. With the deep rooting and reduced row spacing, he obtained increased yields with half the usual number of irrigations.

The value of subsoiling before seedbed preparation is usually nullified by later tillage, and subsoiling after plant emergence has sometimes reduced bean yields because of mechanical damage to roots. Also, subsoiling after emergence tends to push bean rows out of line, making later cultivation difficult. In fine-textured soils of high moisture-holding capacity, hilling up the soil around the plant stems promotes development of adventitious roots on the hypocotyls and thus also helps counteract effects of root rot.

In general, *Fusarium*-resistant beans tolerate cold soils, drought, and soil compaction better than susceptible ones in *Fusarium*-infested soil. Flooding, however, tends to nullify resistance to *F. solani* f. sp. *phaseoli*. Beans tolerant of each of these stress factors have been reported. Several breeding programs in the United States and abroad are establishing one or more of these tolerances in *P. vulgaris*. Improved tolerance to any of these stress factors, especially when combined with *Fusarium* resistance, should contribute to the control of Fusarium root rot.

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