Genetic and Cultural Control of Fusarium Root Rot in Bush Snap Beans

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ABSTRACT

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Deep subsoiling, narrow row spacing, and the use of resistant cultivars increased seed yields of bush snap beans (*Phaseolus vulgaris*) grown in fields infested with *Fusarium solani* f. sp. *phaseoli,* the principal causal agent of root rot. Deep subsoiling was more effective than narrow row spacing in increasing seed yields. Irrigation at 50% vs. 60% available soil moisture did not reduce seed yields. Because of its high genetic resistance to Fusarium root rot, bean line FR-266 had a seed yield almost double that of susceptible cultivar Blue Mountain under most combinations of cultural practice treatments. Growing resistant FR-266 combined with subsoiling, narrow rows, and irrigation after 50% available soil moisture depletion raised 3-yr mean seed yields to 2836 kg/ha, which was 310% of the yield for susceptible Blue Mountain grown under standard cultural practice conditions.

Common beans in the United States are often divided into two major categories: dry beans (pinto, navy, etc.) which are harvested as dry, mature seed before food preparation, and snap beans in which the immature pod is consumed as a vegetable. Snap bean seeds are usually used only for planting. Root rot caused by *Fusarium solani* (Mart.) Sacc. f. sp. *phaseoli* (Burkholder) W. C. Snyder & H. N. Hans. is one of the most widespread and destructive diseases of beans (*Phaseolus vulgaris* L.), especially in the northwestern seed production areas (7) and the northeastern processing areas. Other root rot pathogens, such as *Rhizoctonia solani* Kühn, *Pythium ultimum* Trow, and *Thielaviopsis basicola* (Berk. & Broome) Ferraris, are often present in these areas; however, they are associated primarily with stand establishment problems that can be controlled with seed fungicide treatments (2,7). Fusarium root rot cannot be controlled effectively by seed treatment and becomes chronically more pervasive throughout the root system over time (5).

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Environmental stress factors predispose the crop to severe root rot and lower yields. These factors include soil compaction (13,23), root anoxia caused by periodic overwatering (7,13,15,16), drought (7,14), and overdense plantings that produce severe interplant competition (3,7,9). Compaction reduces emergence (1), nodulation and N_2-fixation, and plant growth (24). It also restricts disease-weakened roots (4,8,13,14) to the top 30 cm of soil (above the dense plow sole layers) where most of the root-rotting organisms are found (6).

Yields of bush snap beans grown for processing (11,25) or seed production (10,27) have increased when plants were arranged with equidistant spacings of 15.25 cm between rows and between plants in each row, an arrangement sometimes called high-density culture. Although this system gives a population of 430,455 plants per ha (compared to 411,053 per ha in standard spacing), interplant competition is actually reduced in spite of the slightly higher population density. The standard spacing for western bush snap bean seed production is 5 cm between seed (21 plants per m) in rows planted 56 cm apart. Because of the resulting rectangular spacing arrangement, plants within a row have severely overlapping roots and canopies. This overlap results in strong competition for light, water, and nutrients within the row, while the water and nutrients between the rows may be largely underutilized. Wide row spacing also exposes the soil to sunlight until late in the season; this exposure encourages weed growth.

Dry bean cultivars (most of which are vine types) with genetic resistance to Fusarium root rot (7,18) outyield susceptible cultivars in field soils infected by *F. solani* f. sp. *phaseoli.* Resistance to the pathogen is not complete, however, and adverse environmental conditions favoring root rot can reduce yields among resistant cultivars (7,18). In the dry-bean production area of central Washington, cultural practices such as deep tillage, proper irrigation, and chemical seed treatments complement and help stabilize genetic resistance in an integrated disease control system (7,18).

In the western seed-producing states, dry beans are usually planted in rows 56 cm apart with 8–10 seeds per row (12–16 seeds per m) (7). Dry beans with viny growth habits usually do not respond favorably to high-density culture, presumably because of the compensatory ability of vines to fill the space between rows (10). The viny habit is also the reason why dry beans do not need to be planted as densely (8–10 cm between seeds) as bush snap beans (5 cm between seeds).

Beans with a bush growth habit are generally regarded as having yield potentials inferior to those of viny cultivars. Part of this difference may be due to the vigorous and extensive root system of vine types. The more vigorous its root system, the more a cultivar can exploit available soil moisture and nutrients. If soil compaction is reduced by subsoiling, roots can grow freely in depths of 30–100 cm where there are fewer propagules of root pathogens than in the top 30-cm zone (6,7,13,18), as well as additional soil moisture and nutrients.

Studies of irrigation requirements for production of bush snap bean seed show that highest yields are obtained when available soil moisture is kept at about 60% (12). Many of the soils in central Washington are medium- to coarse-textured (45–85% sand) containing little organic matter (≤1/2%) and with a relatively low water-holding capacity (about 2.5–3.0 cm per 30 cm of soil)(17). Evapotranspiration during the bloom and pod fill periods in July and August may exceed 0.75 cm per day. As a result, a bean field with a dense plow sole that restricts root growth to a 30-cm depth might need irrigation every 3–4 days to prevent periodic moisture stress. Most growers irrigate every 5–7 days or every 8–10 days with finer-textured soils. Both periodic short-term drought and overirrigation predispose dry beans to Fusarium root rot injury which may cause reduced yields (15,16).

Bush snap beans resistant to Fusarium root rot have been developed only recently (21). Although vine-type *Fusarium*-resistant and *Fusarium*-susceptible dry beans have been studied, none of the studies have compared seed production of resistant and susceptible bush snap bean cultivars. We are unaware of any studies that determine how bush snap beans in a *Fusarium*-infested field respond to compaction, less-competitive spacing arrangements, or differential irrigation management. Our 3-yr field study is the first known attempt to evaluate the combination of genetic resistance in bush snap beans with cultural practices known to minimize the impact of Fusarium root rot in viny dry beans.

MATERIALS AND METHODS

Field studies were conducted near Prosser, Washington, from 1984 to 1986 on a Warden loam (coarse-silty, mixed, mesic Xerollic Camborthids) containing about 45% sand and 9% clay, with a nonrigid matrix but a distinct plowpan at 25–35 cm (13). We compared the following in all combinations: two cultivars (one resistant and one susceptible to Fusarium root rot); two tillage practices (compacted soil and subsoiling to 50 cm between alternate rows); two interrow spacings (28 and 56 cm) while holding seeding rate constant; and irrigation at 50 and 60% available soil moisture.

Genotypes. Bush bean lines resistant to curly top and bean common mosaic viruses were used. The *Fusarium*-resistant breeding line FR-264 was used in 1984, while a nearly identical sister selection, FR-266 (21), was used in 1985 and 1986. The *Fusarium*-resistant (FR) lines mature about one week later than the susceptible cultivar Blue Mountain, with which they were compared (22). Seed was treated with captan at 2 g/kg in 0.5% methyl cellulose to control Pythium seed rot.

Field compaction and subsoiling. At least three bean crops had been grown during the previous seven seasons on each of the fields used in the study. In addition, the most recent of those bean crops must have had serious damage caused by Fusarium root rot. Fertilizers (nitrogen, phosphorus, zinc) were broadcast at rates determined by soil testing before plowing. The soil was uniformly compacted in the entire field by making multiple passes with a large tractor with dual rear tires; closely spaced tire tracks were run in three directions. Subsoiling to a depth of 45–50 cm between alternate rows was done just before planting. This placed a subsoil mark about 28 cm from each row in the four-row plots, and about 14 cm from each row in the six-row plots. A single-axle, loose-wheel roller was pulled behind the subsoiler to smooth the surface for planting.

Row spacing and planting rates. Standard four-row plots (9.1-m rows spaced 56 cm apart) were planted at the rate of 24 seeds per m (3.8 cm between seeds) per row. The two center rows were used for collecting data. Six-row plots (9.1-m rows spaced 28 cm apart) were planted at the rate of 12 seeds per m (7.6 cm between seeds) per row. The four inner rows of the six-row plots were used for collecting data. These rows had the same total area (10.2 m^2) and seeding rate (469,775 seeds per ha) as the inner two rows of the four-row plots.

Irrigation. In the test fields, the available soil moisture in the top 90 cm of soil was about 5 cm per 30 cm. The fields were preirrigated to capacity 3–4 days before herbicide application and planting. Recommended herbicides (Eptam at 3.4 kg a.i./ha and Treflan at 0.6 kg a.i./ha) were incorporated to a depth of 8–10 cm using a rototiller. After planting, a solid-set sprinkler system was installed with full-circle sprinklers at the corners of square (9.1 × 9.1 m) plots. All plots were given two uniform, light (1.27 cm) irrigations to provide non-stressed conditions until about 10 days before bloom. Thereafter, irrigation treatments were applied when available soil moisture reached either 60% (about every 4–5 days) or 50% (about every 8–10 days). Evaporation (Ep) from a class A weather bureau pan was used to estimate evapotranspiration (ET); we found that ET = 0.95 Ep.

Experimental design and statistical analysis. Two nonreplicated irrigation treatments were established (50% or 60% available soil moisture). Within each irrigated area, seven replications of other treatments were applied as a 2 × 2 × 2 factorial in a randomized complete-block design with genotypes (Blue Mountain or FR-266) as whole blocks, tillage (subsoiling or compaction) as subplots, and row spacing (28 or 56 cm) as sub-subplots. Data for each season and the cumulative 3-yr summaries were subjected to analysis of variance as a four-factor factorial, split-split plot experiment.

Data collection. Total stand counts were taken about 30 days after planting (DAP). Plants were rated for hypocotyl root rot on a 0–5 scale in which 0 = no disease; 1 = a few longitudinal, reddish lesions; 2 = moderate numbers of scattered surface lesions; 3 = numerous coalesced surface lesions and (usually) some internal infection; 4 = severe surface lesions and internal damage; and 5 = dead or dying (20). Ten plants from each replicate were pulled at early bloom stage, about 35–45 DAP. Their dry weights were obtained after being kept for 72 h at 38 C. Mature plants (80% of pods in buckskin stage) were pulled, dried in windrows, and harvested with a rubber-belt thresher (19). Seed weights (adjusted to 10% moisture) were obtained from plants in the two or four center rows of each plot.

In 1985, soil strength in subsoiled and compacted plots was compared by taking penetrometer readings before bloom in a uniformly irrigated field. Readings were taken at 3.5-cm increments to a depth of 52.5 cm. Three penetrometer readings per plot were taken within the plant rows of each treatment. Since differential irrigation had not yet begun, we combined the 7 replicates from each of the two irrigation treatments for analysis.

RESULTS

Emergence. Emergence of FR-266 averaged 7.7% higher than that of Blue Mountain in two of the three years tested (Table 1). Mean emergence in rows

Table 1. Annual and 3-yr emergence means of bush snap beans by principal paired cultural-practice treatments in fields infested with *Fusarium solani* f. sp. *phaseoli*

Factor	Paired treatments	Percent emergence			
		1984	1985	1986	3-yr
Genotype[u]	FR	76.5[v]	67.20**[w]	93.2**	78.9**
	BM	89.3**	59.50	64.7	71.2
Tillage[x]	SS	81.4	57.60	78.6	72.6
	CP	84.4	69.10**	79.3	77.6**
Spacing[y]	28	85.5**	66.60**	81.4**	77.9**
	56	80.3	60.00	76.5	72.3
ASM[z]	50	83.1	65.60*	78.0	75.6
	60	82.7	61.10	80.0*	74.6
Mean		82.9	63.34	79.0	75.1
cv (%)		8.9	13.9	8.2	10.8

[u]BM = Blue Mountain (susceptible); FR = FR-264 in 1984 and FR-266 in 1985 and 1986 (both resistant).
[v]Yearly means based on seven replications.
[w]* = Paired treatment means are significantly different ($P = 0.05$) by analysis of variance; ** = paired treatment means are significantly different ($P = 0.01$) by analysis of variance.
[x]SS = Deep subsoiling between alternate rows to a depth of 50 cm; CP = compacted field plots.
[y]28 = 28-cm row spacing with 12 seeds per m; 56 = 56-cm row spacing with 24 seeds per m.
[z]Available soil moisture. Treatments are replacement irrigation at 50% or 60% ASM.

spaced 28 cm apart was 5.5% higher than that in rows 56 cm apart, and rank was consistent each year. Rows spaced 28 and 56 cm apart averaged 9.3 and 17.4 seedlings per m respectively, which was close to the desired 1:2 ratio. Over 3 yr, mean seedling emergence averaged 5% higher in compacted plots than in subsoiled plots, although differences within a year were significant only in 1985. Available soil moisture treatments did not affect emergence because the differential irrigations were not begun until after emergence.

Disease index at bloom. In two out of three years, the severity of hypocotyl rot was higher for Blue Mountain than for FR-266 (Table 2). The 3-yr mean disease index was 3.1 for Blue Mountain and 2.9 for FR-266. Plants in subsoiled plots had a higher disease index than those in compacted plots in two out of three years; the 3-yr means were higher for subsoiling (3.1) than for compaction (2.8). The 28-cm row spacing resulted in a higher disease index than did the 56-cm row spacing in one out of three years and in the 3-yr means. There were no significant differences between the 3-yr disease index averages for irrigation regimes that maintained 50% or 60% available soil moisture.

Plant weight at bloom. Dry weights at bloom (tops, roots, total) varied highly from year to year. Ten-plant mean total weights were 51 g in 1984, 30 g in 1985, and 57 g in 1986 (data not shown). In general, paired-treatment means within years were not statistically different. The exception was subsoiling, which produced significantly larger plants in two out of three years. Total dry weight of FR-266 (55 g) plants was significantly greater than that of Blue Mountain (47 g) in only one of the three years. The tops of plants in subsoiled plots had higher weights than those in compacted plots in two of the three years, but root weights were higher in only one of the three years (data not shown). Roots of FR-266 were significantly heavier than roots of Blue Mountain in all years, with a 3-yr average difference of 23%. Neither available soil moisture nor row spacing caused significantly different top, root, or total dry weight means (Table 3).

Seed yield. Seed yields (data not shown) were highly variable from year to year, but the effects of the 16 treatment combinations were consistent over the 3-yr period. Yields in 1986 were extremely low because of a prolonged hot period from bloom to near maturity. The 3-yr means (Table 4) for yields from the various combinations of genotype and cultural practices ranged from a low of 914 kg/ha to a high of 2836 kg/ha. The low yield was that for susceptible Blue Mountain planted with 56-cm row spacing in compacted, *Fusarium*-infested soils irrigated every 4–5 days (60% available soil moisture). The high figure was for resistant FR-266 planted with 28-cm row spacing in subsoiled, *Fusarium*-infested soils irrigated every 8–10 days (50% available soil moisture).

Table 5 shows the order of paired-treatment effects. Genotype had by far the greatest impact, with FR-266 showing a 95% gain in yield over Blue Mountain. Seed yields for subsoiled plots were 31% higher than those for compacted plots over the 3-yr period. With 28-cm row spacing, plants averaged 11% more seed than those with 56-cm row spacing, but the differences were highly significant in only two of the three years. Irrigation treatment did not affect seed yields.

The susceptible cultivar Blue Mountain responded positively and consistently to subsoiling (Table 6), with a significant 3-yr average gain in seed yield of 429 kg/ha over plants grown in compacted soil. There were no significant yield differences in Blue Mountain caused by differences in irrigation or row spacing when results were averaged over 3 yr.

The *Fusarium*-resistant cultivar FR-266 likewise responded positively to subsoiling, with an average gain of 522

Table 2. Annual and 3-yr mean hypocotyl disease indices of bush snap beans planted in fields infested with *Fusarium solani* f. sp. *phaseoli* as affected by principal paired cultural-practice treatments

Factor	Paired treatments	Hypocotyl disease indices 1984	1985	1986	3-yr
Genotype[u]	FR	3.2[v]	2.7	2.7	2.9
	BM	3.6**[w]	3.0**	2.7	3.1**
Tillage[x]	SS	3.4	3.1**	2.7*	3.1**
	SP	3.3	2.6	2.6	2.8
Spacing[y]	28	3.4	2.9	2.8**	3.0**
	56	3.3	2.8	2.6	2.9
ASM[z]	50	3.3	2.6	2.8**	2.9
	60	3.4	3.1**	2.6	3.0
Mean		3.4	2.9	2.7	3.0
cv (%)		10.0	8.2	9.0	9.3

[u]BM = Blue Mountain (susceptible); FR = FR-264 in 1984 and FR-266 in 1985 and 1986 (both resistant).
[v]Yearly hypocotyl disease index on a 0–5 scale based on seven replications: 0 = no disease; 1 = trace amounts of longitudinal, reddish lesions; 2 = moderate numbers of scattered surface lesions; 3 = numerous coalesced surface lesions, usually with some internal infection; 4 = severe surface lesions and internal damage; 5 = dead or dying.
[w]* = Paired treatment means are significantly different ($P = 0.05$) by analysis of variance; ** = paired treatment means are significantly different ($P = 0.01$) by analysis of variance.
[x]SS = Deep subsoiling between alternate rows to a depth of 50 cm; CP = compacted field plots.
[y]28 = 28-cm row spacing with 12 seeds per m; 56 = 56-cm row spacing with 24 seeds per m.
[z]Available soil moisture. Treatments are replacement irrigation at 50% or 60% ASM.

Table 3. Three-year mean plant dry weights (at bloom) of bush snap beans as affected by principal paired cultural-practice treatments in fields infested with *Fusarium solani* f. sp. *phaseoli*

Factor	Paired treatments	Weight of 10 plants (g) Top	Root	Total
Genotype[u]	FR	42.8*[v,w]	5.2**	48.0*
	BM	39.8	4.2	44.0
Tillage[x]	SS	45.4**	4.9*	50.3**
	CP	37.1	4.5	41.7
Spacing[y]	28	42.0	4.8	46.9
	56	40.5	4.6	45.1
ASM[z]	50	41.7	4.6	46.3
	60	40.9	4.8	45.7
3-yr mean		41.3	4.7	46.0
cv (%)		31.8	29.1	30.5

[u]BM = Blue Mountain (susceptible); FR = FR-264 in 1984 and FR-266 in 1985 and 1986 (both resistant).
[v]* = Paired treatment means are significantly different ($P = 0.05$) by analysis of variance; ** = paired treatment means are significantly different ($P = 0.01$) by analysis of variance.
[w]Means based on 21 replications (seven replications per year).
[x]SS = Deep subsoiling between alternate rows to a depth of 50 cm; CP = compacted field plots.
[y]28 = 28-cm row spacing with 12 seeds per m; 56 = 56-cm row spacing with 24 seeds per m.
[z]Available soil moisture. Treatments are replacement irrigation at 50% or 60% ASM.

kg/ha over the 3-yr period. The response of FR-266 to 28-cm row spacing was also positive, with an average yield gain over the 3-yr period of 334 kg/ha over plants grown under 56-cm row spacing. As with Blue Mountain, soil moisture replacement level (50% or 60%) did not have a consistently significant effect on FR-266. Overall, the 3-yr average yields of FR-266 were about double those of Blue Mountain under any given treatment combination.

Seed weights. The 100-seed weights (10% moisture) were taken only in 1985 and 1986 (data not shown). Mean weights across all treatments were 31.2 g for 1985 and 21.9 g for 1986 ($P < 0.01$). Paired-treatment means for genotype and tillage were consistently different in both years. FR-266 seeds weighed an average of 27.8 g per 100 seeds, while Blue Mountain averaged 25.3 g per 100 seeds ($P < 0.01$). The 2-yr mean of 100-seed weights from subsoiled plots was 27.0 g; the mean from compacted plots was 26.1 g ($P < 0.05$). Row spacing and available soil moisture treatments did not produce consistent effects on seed weight. In spite of the differences in seed yields and 100-seed weights (presumably caused by high temperature stress), there was a high correlation ($r = 0.92$) between seed yield and 100-seed weights across all of the 16 treatments (data not shown) over the 2-yr period.

Soil strength. The effects of compaction and subsequent subsoiling on relative differences in soil strength are illustrated by 1985 data in Fig. 1. Soil strength readings of less than 1 MPa were recorded for all subsoiled plots to a depth of about 0.3 m. The comparable compacted plot soil strengths were near or greater than 2 MPa. At 0.5 m, soil-strength values were again equal. Apparently less soil fracturing takes place as the depth of the subsoil tines is approached.

Table 4. Three-year mean seed yields for two bush snap bean genotypes as affected by 16 combinations of cultural-practice treatments in fields infested by *Fusarium solani* f. sp. *phaseoli*

Genotype	Tillage[w]	Spacing[x]	Available soil moisture (%)	Yield (kg/ha)[y]
FR-264/FR-266 (resistant)[z]	SS	28	50	2,836 a
	SS	28	60	2,663 ab
	SS	56	60	2,464 bc
	SS	56	50	2,412 bcd
	CP	28	60	2,336 cd
	CP	28	50	2,163 de
	CP	56	50	1,985 ef
	CP	56	60	1,803 f
Blue Mountain (susceptible)	SS	28	60	1,477 g
	SS	56	50	1,434 g
	SS	28	50	1,403 g
	SS	56	60	1,357 gh
	CP	28	50	1,107 hi
	CP	56	50	1,011 i
	CP	28	60	933 i
	CP	56	60	914 i

[w]SS = Deep subsoiling between alternate rows; CP = compacted field plots.
[x]28 = 28-cm row spacing with 12 seeds per m; 56 = 56-cm row spacing with 24 seeds per m.
[y]Means followed by same letter are not significantly different ($P = 0.05$) as determined by Duncan's multiple range test. Means based on 21 replications (seven per year).
[z]FR-264 in 1984 and FR-266 in 1985 and 1986.

Table 5. Annual and 3-yr means of bush snap bean seed yields as affected by principal paired cultural-practice treatments in fields infested with *Fusarium solani* f. sp. *phaseoli*

Factor	Paired treatments	Mean seed yield (kg/ha) 1984	1985	1986	Mean
Genotype[u]	FR	2,663**[v,w]	3,393**	941**	2,333**
	BM	1,212	1,938	464	1,205
Tillage[x]	SS	2,341**	2,909**	767**	2,006**
	CP	1,534	2,422	637	1,531
Spacing[y]	28	2,053**	2,839**	703	1,865**
	56	1,824	2,492	702	1,672
ASM[z]	50	2,170**	2,638	574	1,794
	60	1,706	2,694	830**	1,743
Mean		1,938	2,666	702	1,769
cv (%)		24.0	21.4	13.7	24.8

[u]BM = Blue Mountain (susceptible); FR = FR-264 in 1984 and FR-266 in 1985 and 1986 (both resistant).
[v]** = Paired treatment means are significantly different ($P = 0.01$) by analysis of variance.
[w]Yearly means based on seven replications.
[x]SS = Deep subsoiling between alternate rows to a depth of 50 cm; CP = compacted field plots.
[y]28 = 28-cm row spacing with 12 seeds per m; 56 = 56-cm row spacing with 24 seeds per m.
[z]Available soil moisture. Treatments are replacement irrigation at 50% or 60% ASM.

DISCUSSION

Seed yields were increased significantly by deep subsoiling. Accordingly, subsoiling should be considered in programs to control root rot in compacted *Fusarium*-infested fields. Because FR-266 plants in our study also responded positively to 28-cm row spacing, close row spacing (with wider-spaced plants within the row) may be more suitable for use with resistant cultivars. Since neither genotype responded consistently to differences in available soil moisture, growers should be able to reduce production costs by extending irrigation intervals for subsoiled fields to 8–10 days.

FR-266 responded more favorably than Blue Mountain to cultural practices that relieved plant stresses (Table 4). The low-stress treatments of FR-266 (subsoiling, 28-cm row spacing, 50% available soil moisture) outyielded the high-stress treatments of Blue Mountain (compaction, 56-cm row spacing, 60% available soil moisture) by 310% over the 3-yr period. The worst FR-266 treatment combination (compaction, 56-cm row spacing, 60% available soil moisture) yielded 1803 kg/ha; the best treatment combination of Blue Mountain (subsoiling, 28-cm row spacing, 60% available soil moisture) yielded 1477 kg/ha. The difference between these results (326 kg/ha) is significant ($P = 0.05$).

We cannot give reasons for the decreased emergence in subsoiled plots. The 5% increase in emergence (Table 1) in compacted soils may be because of better seed-soil contact, or perhaps subsoiled plots were drier near the surface because tillage disturbance exposed more soil surface to dessication. However, the yield benefits (475 kg/ha) of subsoiling more than offset the slight loss of stand.

It is also hard to account for why 28-cm row spacing increased seedling emergence by 5.5% over that for 56-cm row spacing. Perhaps the proximity of seeds within the row (12 seeds per m in 28-cm row spacing, 24 seeds per m in 56-cm row spacing) increased the opportunity for pathogens in a rotted seed to contaminate nearby seeds.

The increased disease indices for 28-cm row spacing and subsoiled tillage treatments (Table 2) seem inconsistent with the increased yields resulting from these treatments (Tables 4–6). However, this inconsistency points out the error in using a hypocotyl disease index to predict potential yield of a field crop when, as Burke and Barker (5) pointed out, infection by *F. solani* f. sp. *phaseoli* on the lateral roots has more effect on yield than hypocotyl rot. Unfortunately, it is far easier to examine hypocotyl disease symptoms than to examine an entire root system. If roots are free to penetrate below the compacted zone, where more water and nutrients are available and there are fewer propagules of *F. solani* f. sp. *phaseoli,* then a plant can yield more seed in spite of hypocotyl infection. Subsoiled plots allowed direct access to deeper rooting, while the plants grown under 28-cm row spacing were consistently (but insignificantly) more vigorous (Table 3); thus, plants in subsoiled plots may have been able to access more water and nutrients and, thereby, yield more seed.

The inconsistent or low correlations (or both) between seed yields and emergence, hypocotyl disease index, and plant weights at bloom suggest that these criteria are not reliable indicators of how bush snap beans will yield in *Fusarium*-infested fields. However, the consistent positive correlation between seed weight and yield ($r = 0.92$) suggests a possibly more sensitive measure of the degree of total stress (biotic and abiotic) on a crop. This relationship should be studied in more detail.

The effectiveness of subsoiling in reducing soil compaction (Fig. 1), and the subsequent favorable responses of the two snap bean genotypes (Tables 2–4) are in complete agreement with research reports on cotton (23) and vine-type dry beans (8,14,24). Loosening of compacted soils, especially in fields infested with *F. solani* f. sp. *phaseoli,* appears to be a mandatory cultural practice in central Washington to achieve maximum snap bean seed yield potential.

The level of genetic resistance to Fusarium root rot in FR-266 seems high enough across a range of cultural practice treatments to make this genotype highly useful for central Washington production conditions and in breeding programs (21). The higher yield potential of FR-266 in *Fusarium*-infested fields may be caused by the additive effects of *Fusarium* resistance, higher tolerance to soil compaction, and a favorable response to equidistant plant spacing. Part of the improved performance of FR-266 seems to be a result of its consistently large root system with which it can utilize available nutrients and water from a larger volume of soil than that accessible to cultivars with restricted root systems. The relationship of root size and vigor in *Fusarium*-resistant and *Fusarium*-sensitive cultivars should also be studied in greater detail.

The lack of a consistent response to differing available soil moisture levels maintained by irrigation suggests that the

Table 6. Comparison of 3-yr mean seed yields of two bush snap bean genotypes according to differences in principal paired cultural-practice treatments in fields infested with *Fusarium solani* f. sp. *phaseoli*

Paired treatments	Genotype: Blue Mountain	Genotype: FR-264/FR-266[v]	Difference between paired treatment means
Tillage[w]			
SS	1,418[x]	2,594	1,176**[y]
CP	991	2,072	1,081**
Difference	429**	522**	...
Spacing[z]			
28	1,230	2,500	1,270**
56	1,179	2,166	987**
Difference	51	344**	...
Available soil moisture			
50	1,239	2,350	1,111**
60	1,170	2,316	1,146**
Difference	68	34	...
Mean	1,205	2,333	1,128**
cv (%)	27.2	22.6	...

[v]FR-264 in 1984 and FR-266 in 1985 and 1986.
[w]SS = Deep subsoiling between alternate rows to a depth of 50 cm; CP = compacted field plots.
[x]3-yr means based on 21 replications (seven per year).
[y]** = Paired means within a genotype (vertical) or within a cultural-practice treatment (horizontal) are significantly different ($P = 0.01$) by analysis of variance.
[z]28 = 28-cm row spacing with 12 seeds per m; 56 = 56-cm row spacing with 24 seeds per m.

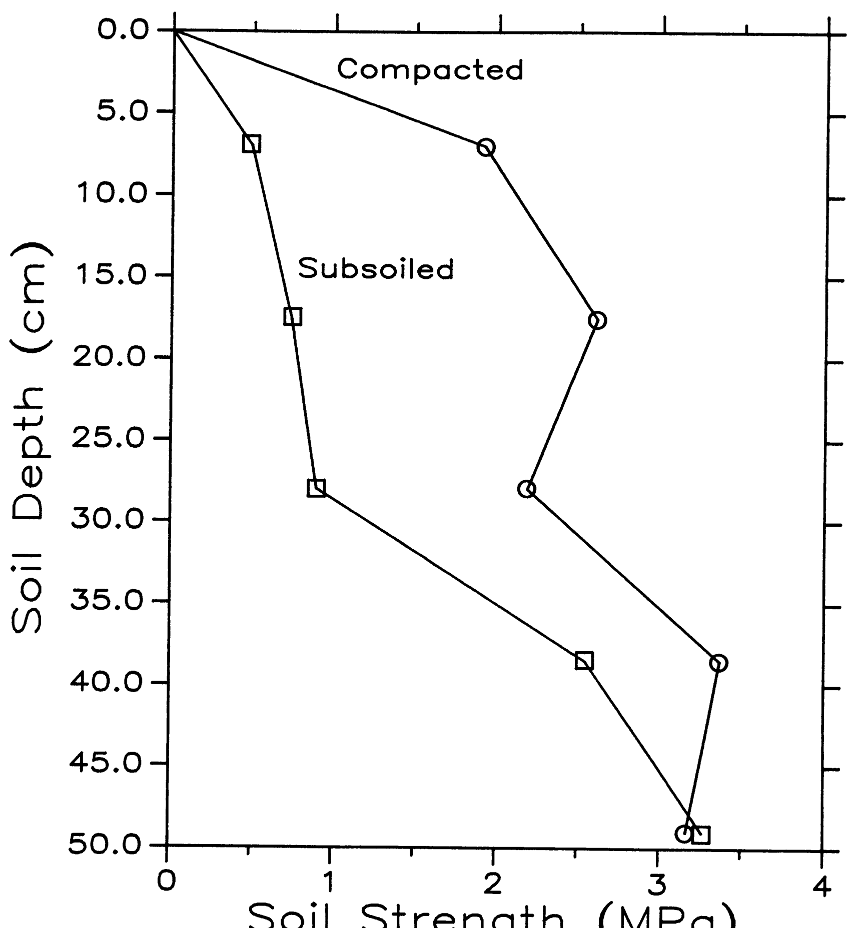

Fig. 1. Soil strength profiles in a Warden loam bean field as affected by compaction and subsoiling. Penetrometer readings (three per plot) were taken 12 June 1985 within plant rows in 14 replicates of each treatment before bloom in a uniformly irrigated field. Field was uniformly compacted by tractor tires in three directions after herbicide incorporation and subsoiled to 50 cm between rows before planting 14 May 1985.

longer interval of 8–10 days between irrigations (replacement at 50% available soil moisture) might allow more soil surface drying in subsoiled fields than does the shorter interval of 4–5 days (replacement at 60% available soil moisture) and thus help to control white mold (*Sclerotinia sclerotiorum* (Lib.) de Bary)(18,26). Use of this irrigation regime may be particularly relevant with FR-266 since the cultivar is in itself somewhat resistant to white mold (21).

The positive response of FR-266 to 28-cm row spacing suggests that it would be suitable for high-density culture and direct mechanical seed harvesting by a pod-stripping, rubber-belt thresher (19). Direct harvesting of standing plants would avoid the weathering and shattering problems inherent with the present windrow system, and allow higher seed yields and seed quality.

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