Eur J Plant Pathol (2011) 131:179–195
DOI 10.1007/s10658-011-9798-y

Large-scale assessment of agricultural practices affecting Fusarium root rot and common bean yield

Bita Naseri · Alireza Marefat

Accepted: 18 April 2011 / Published online: 19 June 2011

Abstract The relationships between a number of agronomic practices, Fusarium root rot (FRR) measurements and yield variables were characterized at different growth stages in 122 commercial bean fields in Zanjan, Iran. Mean FRR incidence, severity and index differed among growth stages and years. A lower FRR index at growth stage R9 and higher yields were detected in Red beans compared to Pinto and White beans. FRR severity affected the number of pods and seeds per plant. Despite the lack of an impact of initial drought on FRR and yield factors, FRR levels were higher following frequent irrigations at 2–3 days intervals than at longer intervals at R6-7. The highest FRR index at R6-7 (51.9%) and incidence at R9 (69.1%) were associated with the densest category of plant populations. Yield components differed significantly between the levels of plant density at R9. FRR levels at V3 were lower for June plantings than for May-second-week plantings. Lower FRR ratings and higher yields were detected at a seeding depth of 0–5 cm in comparison to 10–20 cm. At R9, FRR levels on beans following maize were lower than those following barley, bean, tomato or wheat. At V3, FRR severity was greater in fields that received 50–500 kg/ha of urea compared to non-fertilized fields. Greater mean FRR index at R6-7 and lower yield levels were associated with the greatest weed density compared to weed-free fields. This new information benefits the systematic understanding of interactions between bean yield, FRR and various agronomic variables at large-scale.

Keywords *Fusarium solani* · Linear mixed models · *Phaseolus vulgaris* · Regression

B. Naseri (✉)
Department of Plant Protection, Agricultural & Natural Resource Research Center,
Zanjan, Iran
e-mail: b.naseri@zre.ir

A. Marefat
Department of Plant Protection, Faculty of Agriculture, Zanjan University,
Zanjan, Iran

Introduction

Local varieties of common bean (*Phaseolus vulgaris*) are cultivated on about 7,300 ha of irrigated land with an average production of approximately 2.3 t/ha in Zanjan province (Anonymous 2005). The main classes of common dry bean in Zanjan include Red (Kidney), Pinto (Mottled), and White (Navy) beans. An earlier investigation (Naseri 2008) reported that root rot diseases, caused by *Fusarium solani* in a complex with *Rhizoctonia solani*, and *Macrophomina phaseolina*, threatened the production of bean crops in Zanjan. Estimates of yield losses averaged from 3.3 to 67.0% reductions in pod numbers per plant and 3.8–76.0% fewer seeds per plant, based on incidences of root rot disease of 4.7–95.0% in bean fields (Naseri

2008). Changes in agronomic practices have possibly caused Fusarium root rot (FRR) to become well established in bean fields in the last few years in Zanjan (Naseri 2008) compared to the mid-1990s when province-wide surveys showed the disease occurred at lower levels in the main bean growing region of the province (Moeini and Ahmadi-Nejad 1998). Thus, the disease has the potential to spread further and become more intense, and adversely impact crop production. There are no registered bean cultivars with high levels of resistance to FRR in Iran. The chemical treatment of field soils has been ineffective in controlling FRR (Naseri, unpublished data). Therefore, cultural strategies appropriate to the region need to be identified to reduce yield losses to FRR in Zanjan. An earlier study conducted in production fields in Zanjan showed that disease incidence and severity, yield losses to bean root rots, and frequency of *F. solani* isolated from FRR-affected roots varied with sampling time and location (Naseri 2008). The identification of the agronomic factors responsible for the differences in the crop yield across fields is useful for prioritizing the field-scale research needs to stabilize and improve productivity. Considering disadvantages of confusing effects of different practices, Fernandez et al. (2009) pointed out that surveying commercial fields allows the examination of a large number of crops under various combinations of agronomic factors. Williams et al. (2009) and McDonald et al. (2004) believed that the conclusions drawn from regional studies conducted under various combinations of agricultural and environmental factors improve the efficiency of weed-management systems. It seems that large-scale assessments of various agronomic practices in association with FRR and yield should provide the valuable information, which will benefit field-scale approaches to minimize crop damage. Because of noticeable losses to FRR on susceptible beans under environmental stresses (Harveson et al. 2005), most previous studies have focused on identifying cultural practices that reduce various types of stress on bean crops. Although irrigation regime, nitrogen fertilization, plant and weed density, planting date and depth, and previous cropping history are known to be important factors affecting FRR development and bean production (Abawi and Widmer 2000; Brien et al. 1991; Burke and Miller 1983; Deibert 1995; Kraft et al. 1981), regional assessment of the various agronomic factors linked to FRR at different growth stages is not well documented. Although there have been a number of large-scale investigations describing the associations between agricultural and disease variables (Fernandez et al. 2007; Fininsa and Yuen 2001; Rodríguez et al. 2008; Sahile et al. 2008; Workneh et al. 1999; Zewde et al. 2007), only a few large-scale studies have explored agronomic indicators of yield reductions in pathosystems (Mila et al. 2003). Furthermore, the substantial differences in FRR and yield levels observed between adjacent fields with similar soil and climatic characteristics (Naseri and Marefat, unpublished data) encouraged us to focus on common agricultural operations recommended by local experts and growers to be effective for FRR control and bean yield. Thus, understanding how farmers' agronomic programs correspond with the wide-range diversity in FRR and bean build-up in Zanjan was the aim of this study. We tried to evaluate linkages between a number of agronomic practices, FRR and yield components at V3 (the first trifoliate leaf fully opened, Van Schoonhoven and Pastor-Corrales 1987), R6–7 (from flowering to pod formation) and R9 (pod maturity) growth stages of common bean under environmental conditions in producer's fields of Zanjan.

Materials and methods

Epidemiological surveys

The survey was carried out in the main bean growing region of Zanjan province which is heterogeneous in terms of agricultural factors, crop management, and environmental conditions. Preliminary studies showed that common bean cultivars are grown under a wide range of urea application rates, crops grown in the previous year, dates, depths, irrigation frequencies, plant and weed densities. Assessments of FRR disease were conducted in 122 commercial bean fields (experimental units), ranging from 0.5 to 14 ha in size, from 2008 to 2009 (35 in 2008 and 87 in 2009). Common bean fields were randomly selected across the area and farmers were interviewed for details of agronomic factors regarding bean class, initial drought (the time from seeding to the first irrigation of the field, which ranged from 15 to 45 days), irrigation frequency, planting date, the crop grown in the previous year and urea usage (kg/ha). The same fields were examined for FRR incidence and severity, plant and weed density, and planting depth on three dates, at V3, R6–7 and R9. If required, more than one visit was made to cover a designated growth stage in the fields. To manage a large number of assessments at each sampling time, bean plants at three randomly selected spots (0.25 m^2 quadrat) in each field were counted to determine plant density and then assessed for the disease incidence as the percentage of plants showing FRR symptoms. Weed density was recorded as the number of weed plants per quadrat. To examine disease severity rating, three symptomatic (death, wilt, leaf chlorosis or yellowing) plants per quadrat were dug up carefully and rated using the 0–5 scale based on the percentage of root tissues with discolouration, lesions, or necrosis (Naseri 2008). For each observation (quadrat), a root disease index was determined as follows: disease incidence × disease severity/5 (Naseri 2008). Planting depth, the length of tap roots (cm) from the germinated seeds to the soil surface, was measured on three plants per quadrat. The number of pods and seeds per plant was recorded for three plants per quadrat at R9. To confirm infection by *F. solani*, beans (two plants per quadrat) with symptoms of either longitudinal cracks, red streaks or necrosis on the roots were collected and transferred to the laboratory. The pathogenicity of 94 *F. solani* isolates was tested in a greenhouse located at Agricultural and Natural Resource Research Center in Zanjan. The complete details on the fungal isolation, identification and pathogenicity tests were provided by Naseri (2008). In order to enhance the ability of *F. solani* isolates to cause red streaks (a typical FRR symptom) more rapidly, wound-inoculation was performed as follows. The wound (approx. 3 mm^2) was established by gently scratching the crown of bean seedlings using a clean scalpel, then a spore suspension was poured into the wound, and the remainder of the pathogenicity test was conducted as described by Naseri (2008).

Categorization of fields according to agricultural factors

After a preliminary analysis, the information obtained from the field assessments and the farmers was used to categorize the fields according to the factors (Table 1), which was then used for further analysis to determine the effect of the factors on FRR and yield parameters. For class factor, fields were grouped into three “Pinto”, “Red” and “White” bean classes. Fields were categorized into the two groups, based on whether an initial drought practice was applied to the field (yes = 1) or not (no = 0). For the irrigation program, fields were classified into the four irrigation levels based on the number of (2–9) days between two consecutive irrigating times applied to the field. Bean fields were excluded from the categories of irrigation frequency at V3, if the period of initial drought covered the V3 growth stage (Table 1). In some fields, irrigation patterns applied to the fields changed over the growing season, e.g., some bean growers irrigated their fields at closer intervals at R6-7 and occasionally at R9 in order to increase flowering and thereby enhance seed production. This change was considered in the field categorization if there were at least three subsequent irrigations before the sampling time followed a new pattern. The type of irrigation system in the fields a form of flood irrigation, except for three fields with sprinkler irrigation. Fields were grouped according to the crop that had been grown in the previous year as follows: alfalfa, barley, bean, maize, potato, tomato, or wheat. Based on the data collected, fields were grouped to two levels of FRR incidence or severity, three plant or weed densities, four planting dates, three planting depths, three urea inputs, and two sampling years (Table 1).

Statistical analysis

Data for FRR incidence, severity and index collected from 122 bean fields at the sampling times were subjected to linear mixed modeling using the method of residual maximum likelihood (REML) implemented in GENSTAT version 6.1 (Payne et al. 2002) to examine the effects of class, initial drought, irrigation frequency, plant and weed density, planting date and depth, previous crop, sampling year and urea usage, and interactions with growth stage (as terms in the fixed part of the mixed model). Two-way or higher order interactions between the factors resulted in no estimation due to zero error variance. Therefore, only the two-way interactions of the factors with growth stage were assessed. Growth stage was selected for the interactions in order to compare the means for FRR factors between various levels of agronomic factors tested at the three sampling times.

Table 1 The number of common bean fields (122 in total) under different cultivation systems categorized into levels according to agricultural and disease factors surveyed, 2008–2009

Factors	Factor levels/No. of fields						
Bean class			Red/60		Pinto/23		White/39
Disease incidence			<70%/51				70–100%/71
Disease severity			<4/93				4–5/28
Initial drought			Yes/67				No/55
Irrigation intervals (day)-V3[a]		2–3/0		4/0		5–6/41	7–9/14
Irrigation intervals (day)-R6-7		2–3/17		4/21		5–6/62	7–9/22
Irrigation intervals (day)-R9		2–3/12		4/21		5–6/38	7–9/51
Plant density-V3 [b]		1–4/11			4–8/55		8–17/56
Plant density-R6-7		1–4/19			4–8/91		8–17/12
Plant density-R9		1–4/22			4–8/87		8–17/13
Planting date		May 2nd wk/16		May 3–4th wk/31	Jun 1–2nd wk/59		Jun 3rd wk/16
Planting depth		0–5 cm/41			5–10 cm/55		10–22 cm/26
Previous crop	Alfalfa/6	Barley/6	Bean/24	Maize/6	Potato/5	Tomato/5	Wheat/69
Urea usage (kg/ha)		0/16			1–50/25		50–500/81
Weed density-V3 [b]		0/21			1–15/69		> 16/30
Weed density-R6-7		0/16			1–15/92		> 16/12
Weed density-R9		0/12			1–15/81		> 16/27
Year			2008/35			2009/87	

[a] Irrigation frequency applied to the fields changed over the growth stages and this change was considered in the categorization if at least three subsequent irrigations occurred before the sampling time had followed the new pattern

[b] Density was based on the number of bean or weed plants per quadrat

The form of the random part of the mixed model was Year/Stage/Field/Replicate. Data on pod and seed numbers per bean plant collected from 122 fields at R9 were analyzed using REML to examine the main effects of FRR and agronomic factors as fixed terms. The random part of the mixed model was Year/Field/Replicate. Means for significant fixed model terms were compared using the least significant difference (LSD) between means. All percentage values for disease incidence and index were arcsine square root transformed before further statistical analysis to improve the homogeneity of the variance of the data. Due to the unbalanced data structure (unequal number of fields with different levels of factors), REML and the Wald test (GENSTAT) were used to examine the effects of factors.

Correlations between FRR, yield and agricultural variables were analysed using simple linear regression (GENSTAT). Arcsine-transformed mean values for disease incidence and index, and the means for disease severity, plant and weed density, planting depth, pod and seed numbers per for each field were used in the regression analyses. The criteria used to evaluate the strength of regressions were the coefficient of determination (R^2) and the *P* value. In this study, regression analysis was used to determine the relationships between the variables that contribute to FRR development and bean production rather than to describe models for FRR and yield predictions.

Results

A wide range of variation in the agricultural factors was observed among the 122 bean fields studied from 2008 to 2009. The number of fields with the different levels of the factors examined is presented in Table 1. The sampling year, growth stage and their interactions significantly affected FRR factors, except the effect for the year × stage interaction for FRR incidence was not significant (Table 2). FRR symptoms were evident

Table 2 Effects of agricultural factors on incidence, severity and index of Fusarium root rot assessed from V3 to R9 growth stage in bean fields, 2008–2009

Factor	Disease incidence			Disease severity			Disease index		
Fixed term	Wald statistic	df	*Chi p*	Wald statistic	df	*Chi p*	Wald statistic	df	*Chi p*
Class	13.6	2	0.001	14.8	2	0.001	18.7	2	0.001
Initial drought	0.15	1	0.703	1.9	1	0.174	0.1	1	0.784
Irrigation	46.9	3	0.001	44.4	3	0.001	48.4	3	0.001
Growth stage	41.7	2	0.001	29.1	2	0.001	53.3	2	0.001
Plant density	1.4	2	0.492	13.6	2	0.001	17.3	2	0.001
Planting date	40.3	3	0.001	64.3	3	0.001	61.6	3	0.001
Planting depth	105.1	2	0.001	231.3	2	0.001	191.7	2	0.001
Previous crop	69.6	6	0.001	78.5	6	0.001	78.2	6	0.001
Urea	14.2	2	0.001	42.2	2	0.001	26.0	2	0.001
Weed	5.5	2	0.065	5.4	2	0.067	5.9	2	0.054
Year	3742.2	2	0.001	2704.4	2	0.001	2714.9	2	0.001
Stage.Crop	14.4	12	0.275	10.0	12	0.619	12.5	12	0.403
Stage.Class	10.2	4	0.037	6.7	4	0.15	10.7	4	0.031
Stage.Date	13.9	6	0.031	22.0	6	0.001	14.8	6	0.022
Stage.Density	13.5	4	0.009	4.1	4	0.397	9.4	4	0.052
Stage.Depth	4.9	4	0.303	2.8	4	0.589	3.8	4	0.434
Stage.Drought	1.2	2	0.557	0.34	2	0.842	0.2	2	0.926
Stage.Irrigation	12.8	6	0.047	14.0	6	0.03	12.8	6	0.046
Stage.Urea	4.0	4	0.401	1.9	4	0.749	3.4	4	0.496
Stage.Weed	8.2	4	0.084	8.5	4	0.076	7.5	4	0.110
Stage.Year	0.4	2	0.814	38.5	2	0.001	10.0	2	0.007

in all the 122 bean fields. Mean values for FRR incidence and index at V3, R6-7 and R9 in 2009 were greater ($P<0.05$) than the corresponding values in 2008 (Table 3). In both years, the means of FRR factors at V3 were lower ($P<0.05$) than those at R6-7. The sampling year had no significant effect on the yield factors (Table 4).

Bean class

The main classes of bean grown in the fields studied were Red (49.1%), Pinto (18.9%) and White (32.0%; Table 1). Bean class and its interaction with growth stage significantly affected the disease factors with the exception of FRR severity (Table 2). At R9, mean

Table 3 Incidence (DI), severity (DS) and index (DX) of Fusarium root rot assessed from growth stages V3 to R9 in bean fields, 2008–2009

Sampling time	V3			R6-7			R9		
Factor levels	DI	DS	DX	DI	DS	DX	DI	DS	DX
2008	26.7[a]	1.9	19.6	49.0	3.0	39.0	48.0	1.5	26.9
2009	59.3	2.3	37.3	73.6	3.2	53.2	61.5	2.8	45.8
2008	21.6[b]	–	11.7	66.8	–	44.7	64.6	–	21.9
2009	87.8	–	41.1	99.7	–	75.9	91.4	–	59.6

[a] LSD between arcsine-transformed means of disease incidence and index and the means of disease severity within stage and within year were 10.6 and 14.6 for DI, 0.6 and 0.8 for DS, 8.2 and 11.4 for DX, respectively

[b] Back-transformed means

Table 4 Effects of agricultural and disease factors on yield factors assessed at R9 growth stage in bean fields, 2008–2009

Factor	Pods no. per plant			Seeds no. per plant		
Fixed term	Wald statistic	df	*Chi p*	Wald statistic	df	*Chi p*
Bean class	70.2	2	0.001	65.7	2	0.001
Disease incidence	0.3	1	0.615	0.5	1	0.47
Disease severity	8.2	1	0.004	7.7	1	0.006
Initial drought	2.2	1	0.142	2.6	1	0.105
Irrigation	1.9	3	0.592	2.4	3	0.499
Plant density	39.9	2	0.001	27.4	2	0.001
Planting date	0.2	3	0.975	1.0	3	0.811
Planting depth	7.8	2	0.021	8.3	2	0.016
Previous crop	523.8	7	0.001	357.3	7	0.001
Urea	1.8	2	0.399	1.6	2	0.445
Weed density	9.6	2	0.008	9.1	2	0.011
Year	1.2	1	0.276	1.5	1	0.225

FRR incidence was lower ($P<0.05$) in the Red class than in the White class (Table 5). For disease index at R9, the lowest mean value ($P<0.05$) was observed in the Red class in comparison with the Pinto and White classes. For each class, greater mean FRR incidence, severity and index ($P<0.05$) were detected at R6-7 than at V3 (Table 5). Class affected ($P=0.001$) the number of pods and seeds per bean plant (Table 4). At R9, pod and seed numbers in the Red beans were higher ($P<0.05$) than those of the Pinto and White beans (Table 6).

Disease incidence and severity

The majority of the fields were categorized into the high range of FRR incidence (70–100% in 58.2% of the fields) and into the low range of FRR severity (<4 ratings in 76.2% of fields; Table 1). FRR severity significantly affected the number of pods and seeds per plant (Table 4). Mean pod and seed numbers per plant for the low severity ratings (<4) were higher ($P<0.05$) than those for the high ratings (4–5; Table 6). FRR incidence and severity

Table 5 Incidence (DI), severity (DS) and index (DX) of Fusarium root rot on different bean classes assessed from growth stages V3 to R9 in bean fields, 2008–2009

Sampling time	V3			R6-7			R9		
Factor levels	DI	DS	DX	DI	DS	DX	DI	DS	DX
Red	41.7[a]	2.0	27.7	59.7	3.0	44.1	44.6	1.7	27.5
Pinto	43.5	2.0	28.3	59.4	3.0	45.2	58.2	2.3	40.2
White	43.8	2.3	29.4	64.9	3.3	48.9	61.5	2.5	41.4
Red	50.5[b]	–	23.2	88.5	–	55.8	57.0	–	22.8
Pinto	54.5	–	24.2	88.0	–	58.3	85.8	–	47.3
White	55.2	–	26.0	95.9	–	66.6	91.4	–	49.9

[a] LSD between arcsine-transformed means of disease incidence and index and the means of disease severity within stage and within class were 9.8 and 14.8 for DI, 0.4 and 0.8 for DS, 7.4 and 11.4 for DX, respectively

[b] Back-transformed means

Table 6 Pod and seed numbers per plant at different levels of agricultural and disease factors assessed at R9 growth stage in bean fields, 2008–2009

Factors[a]	Factor levels						
	Pod no./Plant & Seed no./Plant						
Bean class		Red		Pinto		White	
LSD=4.2 & 19.6[b]		22.5 & 88.9		10.1 & 41.0		12.0 & 41.1	
Disease severity rating		<4				4–5	
LSD=2.0 & 8.8		16.2 & 62.8				13.5 & 51.3	
Plant density		1–4		4–8		8–12	
LSD=3.4 & 15.0		21.0 & 80.3		14.2 & 54.8		9.4 & 35.9	
Planting depth		0–5 cm		5–10 cm		10–20 cm	
LSD=4.2 & 19.0		17.4 & 70.4		14.2 & 53.2		13.0 & 47.5	
Previous crop	Alfalfa	Barley	Bean	Maize	Potato	Tomato	Wheat
LSD=9.0 & 41.4	17.6 & 63.7	12.2 & 45.3	13.6 & 47.9	16.8 & 75.8	20.0 & 76.4	9.8 & 41.8	14.2 & 48.3
Weed density		0		1–15		>16	
LSD=4.8 & 21.4		19.3 & 76.5		14.8 & 55.4		10.5 & 39.1	

[a] Only factors with significant effects are presented

[b] left and right numbers refer to LSD values between means of pod and seed numbers per plant, respectively

were negatively correlated ($P<0.05$) with the yield variables (Table 7).

Initial drought

An initial drought was applied in 54.9% of the fields studied in 2008–2009 (Table 1) and had no significant effect on FRR (Table 2) or the yield factors tested (Table 4).

Irrigation frequency

Of the 122 fields studied in this survey only 55 (45.1%) fields were regularly irrigated from right after seeding at 5–9 days intervals (Table 1). The majority of those fields were irrigated at 5–6 days intervals at V3 (74.5% of total 55 regularly-irrigated fields) and R6-7 (50.8% of total 122 fields), whereas at R9 31.2% had this irrigation frequency. Irrigation frequency and its interaction with growth stage affected ($P<0.05$) the FRR factors tested (Table 2). At V3 and R9, the length of irrigation interval had no significant effect on the FRR factors (Table 8). At R6-7, mean values for FRR factors were higher ($P<0.05$) for irrigation at 2–3 days intervals than for those at longer intervals (4–9 days). Under 2–4 days irrigations, mean values for FRR factors were significantly higher at R6-7 than at V3 (Table 8).

Plant density

The number of the fields categorized by plant density changed over the sampling time; so the number of the fields with the highest density (8–17 plant/quadrat) decreased from 56 (45.9%) fields at V3 to 13 (10.7%) fields at R9 (Table 1). Plant density affected FRR severity and index, while its interaction with growth stage significantly affected FRR incidence and index (Table 2). The mean FRR incidence detected at a density of 8–17 plant/quadrat at R9 was significantly greater than those at the lower densities, 1–8 plant/quadrat (Table 9). The mean disease index at R6-7 for the densest level (8–17 plant/quadrat) was greater ($P<0.05$) than that for the intermediate level of 4–8 plant/quadrat. Mean FRR incidence and index for the densest level of bean plants were significantly lower at V3 than at R6-7 and R9. Plant density was negatively correlated ($P<0.05$) with FRR variables at V3 (Table 10). Plant density significantly affected the yield factors (Table 4). The mean values for pod and

Table 7 Relationships between yield components and agricultural and Fusarium root rot variables examined at R9 growth stage in bean fields, 2008–2009

Dependent variable[a]	Independent variable	R^2	df	a (SE)	*P*
Pods no./plant	Disease incidence	0.19	120	−0.16 (0.03)	0.001
Seeds no./plant	Disease incidence	0.19	120	−0.72 (0.14)	0.001
Pods no./plant	Disease severity	0.17	120	−2.87 (0.58)	0.001
Seeds no./plant	Disease severity	0.16	120	−12.77 (2.69)	0.001
Pods no./plant	Irrigation frequency	–	–	–	ns
Seeds no./plant	Irrigation frequency	–	–	–	ns
Pods no./plant	Plant density	0.07	120	−1.25 (0.4)	0.003
Seeds no./plant	Plant density	0.05	120	−4.66 (1.88)	0.014
Pods no./plant	Planting date	–	–	–	ns
Seeds no./plant	Planting date	–	–	–	ns
Pods no./plant	Planting depth	0.07	120	−0.68 (0.24)	0.005
Seeds no./plant	Planting depth	0.07	120	−3.26 (1.07)	0.003
Pods no./plant	Urea usage	–	–	–	ns
Seeds no./plant	Urea usage	–	–	–	ns
Pods no./plant	Weed density	0.09	118	−0.15 (0.05)	0.001
Seeds no./plant	Weed density	0.1	118	−0.73 (0.21)	0.001

[a] Arcsine-transformed means of disease incidence, and the means of pod and seed numbers per plant, disease severity, plant and weed density, and planting depth for three replicate observations per field were used for regression analysis; intercepts were calculated but not presented; R^2 = coefficient of determination; a = estimate of parameter in simple linear regression; *SE* standard error; ns=$P>0.05$

seed numbers per plant were significantly different ($P<0.05$) between the levels of plant density determined at R9 (Table 6). Mean numbers of pods and seeds per plant for the highest plant density were nearly half of the corresponding values for the lowest plant density.

Planting date

The common bean fields surveyed included those seeded by the second week of May (13.1%), the third to fourth week of May (25.4%), the first to second week of June (48.4%), and the third week of June (13.1%; Table 1). The averages (over 2008–2009) of mean monthly air-temperature and total monthly rainfall for May (mid-spring in Zanjan) and June (late spring) were 14.2°C and 21.2 mm, and 18.3°C and 19 mm, respectively. Harvest time in the fields started from mid-August to mid-September with 21–22°C and 16–18°C mean monthly temperatures, respectively (Zanjan Meteorological Office 2009). The planting date of the bean fields and its interaction with growth stage significantly affected FRR factors (Table 2). At V3,

Table 8 Effect of irrigation frequency on incidence (DI), severity (DS) and index (DX) of Fusarium root rot assessed from growth stages V3 to R9 in bean fields, 2008–2009

Sampling time	V3			R6-7			R9		
Factor levels	DI	DS	DX	DI	DS	DX	DI	DS	DX
2–3 days	46.4[a]	2.2	30.7	84.6	4.4	65.9	61.7	2.6	43.9
4 days	46.2	2.0	29.2	62.0	2.9	44.2	54.2	2.2	35.0
5–6 days	39.2	2.1	25.9	56.8	2.8	41.4	53.4	2.0	33.7
7–9 days	40.3	2.0	28.0	41.9	2.2	32.9	49.8	1.9	32.8
2–3 days	61.0[b]	–	28.3	82.0	–	97.0	91.7	–	55.4
4 days	60.5	–	25.7	92.1	–	56.1	78.0	–	36.5
5–6 days	45.1	–	20.3	83.2	–	49.9	76.3	–	33.9
7–9 days	47.5	–	23.7	51.0	–	32.4	68.6	–	32.2

[a] LSD between arcsine-transformed means of disease incidence and index and the means of disease severity within stage and within irrigation were 14.0 and 17.2 for DI, 0.8 and 0.8 for DS, 10.8 and 13.2 for DX, respectively

[b] Back-transformed means

Table 9 Effect of plant density on incidence (DI), severity (DS) and index (DX) of Fusarium root rot assessed from growth stages V3 to R9 in bean fields, 2008–2009

Sampling time	V3			R6-7			R9		
Factor levels	DI	DS	DX	DI	DS	DX	DI	DS	DX
1–4 Plant/Quadrate	49.1[a]	2.4	35.0	58.1	3.2	47.5	44.7	2.1	33.7
4–8 Plant/Quadrate	40.8	1.9	25.5	56.3	2.7	38.9	50.5	1.9	31.6
8–17 Plant/Quadrate	39.1	1.9	24.8	69.5	3.4	51.9	69.1	2.5	43.8
1–4 Plant/Quadrate	67.0[b]	–	36.5	85.6	–	63.4	57.2	–	33.9
4–8 Plant/Quadrate	48.6	–	19.7	82.2	–	44.5	70.1	–	30.0
8–17 Plant/Quadrate	44.9	–	18.6	99.5	–	73.2	99.3	–	55.2

[a] LSD between arcsine-transformed means of disease incidence and index and the means of disease severity within stage and within density were 13.6 and 16.8 for DI, 0.6 and 0.8 for DS, 10.4 and 13.0 for DX, respectively

[b] Back-transformed means

greater ($P<0.05$) mean values for FRR factors were detected for plantings within the second week of May than for those in the first to third week of June (Table 11). Planting within the third week of June had the lowest ($P<0.05$) FRR incidence, severity and index in comparison with the other planting date categories at V3. At R6-7 and R9, mean values for the FRR factors for plantings within June third week were significantly lower than those from second week of May, except for disease incidence at R9. For plantings in June, greater mean disease incidence, severity and index were recorded at R6-7 and R9 than at V3 (Table 11). Planting date was negatively correlated ($P<0.05$) with the FRR variables at V3 (Table 10).

Planting depth

The common bean fields surveyed were seeded at either 0–5 cm (33.6%), 5–10 (45.1%), or 10–22 cm depths (21.3%; Table 1). The depth of seeding in bean fields significantly affected FRR incidence, severity and index (Table 2). At the three growth stages surveyed, mean FRR incidence and index were significantly greater for plantings at 10–22 cm depths than for those at 0–5 cm depths (Table 12). Mean FRR severity was significantly greater for the deepest planting than for shallower ones surveyed, except for the deepest level at R9. FRR index at both V3 and R6-7 was lower ($P<0.05$) for depths at 5–10 cm than those at 10–22 cm. There were significant positively correlations between planting depth and FRR variables at the three growth stages studied (Table 10). The depth of seeding in bean fields affected ($P<0.05$) the yield factors examined at R9 (Table 4). Mean pod and seed numbers per plant for the shallowest seeding depth, 0–5 cm, were greater ($P<0.05$) than those at the deepest seeding depth, 10–20 cm (Table 6).

Previous crop

The most common crop planted before a bean crop was wheat (in 56.6% of the fields), followed by bean (19.7%), alfalfa (5%), barley (5%), maize (5%), potato (4.1%), and tomato (4.1%; Table 1). The crop grown before beans significantly affected FRR incidence, severity and index over the sampling times (Table 2). At R6-7, mean FRR incidence in bean crops grown after potato was greater ($P<0.05$) than for those following maize or barley (Table 13). FRR index at R6-7 was significantly greater for beans grown after potato and tomato than for those grown after maize or barley. At R9, lower ($P<0.05$) mean FRR incidence, severity and index were observed in beans following maize than in those following barley, bean, tomato and wheat, with incidence significantly higher in rotations with tomato than after potato. As the crop planted the year before bean, alfalfa showed a lower ($P<0.05$) mean disease incidence at the last sampling than tomato. Beans grown following alfalfa, barley, potato, tomato and wheat, registered similar FRR levels to bean monocroppings. The preceding crop had a significant effect on the yield factors examined at R9 (Table 4). The mean number of pods per plant following tomato was lower ($P<0.05$) than that after potato (Table 6).

Table 10 Relationships between agricultural and Fusarium root rot variables examined from growth stages V3 to R9 in bean fields, 2008–2009

Dependent variable[a]	Independent variable	V3			R6-7			R9		
		R^2(df)	a (SE)	*P*	R^2(df)	a (SE)	*P*	R^2(df)	a (SE)	*P*
Incidence	Date	0.09 (121)	−0.58 (0.167)	0.001	–	–	ns	–	–	ns
Severity	Date	0.29 (121)	−0.06 (0.009)	0.001	0.04 (119)	−0.02 (0.01)	0.04	–	–	ns
Index	Date	0.18 (121)	−0.65 (0.129)	0.001	–	–	ns	–	–	ns
Incidence	Depth	0.19 (121)	2.5 (0.475)	0.001	0.14 (119)	2.48 (0.565)	0.001	0.23 (121)	3.52 (0.588)	0.001
Severity	Depth	0.49 (121)	0.23 (0.022)	0.001	0.4 (119)	0.23 (0.026)	0.001	0.28 (120)	0.2 (0.029)	0.001
Index	Depth	0.42 (121)	3.01 (0.324)	0.001	0.27 (119)	2.94 (0.444)	0.001	0.27 (120)	3.17 (0.478)	0.001
Incidence	Irrigation	–	–	ns	0.08 (119)	−5.37 (1.63)	0.001	0.04 (121)	−3.51 (1.69)	0.04
Severity	Irrigation	–	–	ns	0.17 (119)	−0.41 (0.085)	0.001	–	–	ns
Index	Irrigation	–	–	ns	0.09 (119)	−4.7 (1.38)	0.001	–	–	ns
Incidence	P Density	0.19 (121)	−3.15 (0.601)	0.001	0.06 (119)	−3.02 (1.12)	0.008	–	–	ns
Severity	P Density	0.12 (121)	−0.15 (0.036)	0.001	–	–	ns	–	–	ns
Index	P Density	0.2 (121)	−2.62 (0.482)	0.001	0.07 (119)	−2.88 (0.948)	0.003	–	–	ns
Incidence	Urea	0.1 (120)	0.1 (0.028)	0.001	–	–	ns	0.05 (121)	0.08 (0.032)	0.011
Severity	Urea	0.21 (120)	0.01 (0.002)	0.001	0.06 (119)	0.004 (0.002)	0.008	0.05 (120)	0.004 (0.002)	0.011
Index	Urea	0.19 (120)	0.11 (0.021)	0.001	–	–	ns	0.05 (120)	0.06 (0.026)	0.018
Incidence	W Density	0.14 (119)	0.22 (0.051)	0.001	0.08 (117)	0.38 (0.121)	0.002	0.09 (119)	0.43 (0.125)	0.001
Severity	W Density	0.07 (119)	0.01 (0.003)	0.003	0.08 (117)	0.02 (0.007)	0.002	0.19 (118)	0.03 (0.006)	0.001
Index	W Density	0.16 (119)	0.19 (0.04)	0.001	0.12 (117)	0.4 (0.101)	0.001	0.21 (118)	0.54 (0.097)	0.001

[a] Arcsine-transformed means of disease incidence and index, and the means of severity rating, plant and weed density, and planting depth in three replicate observations per field were used for regression analysis; intercepts were calculated but not presented here; R^2 = coefficient of determination; a = the estimate of parameter in the simple linear regression; ns = $P>0.05$

Table 11 Incidence (DI), severity (DS) and index (DX) of Fusarium root rot assessed from growth stages V3 to R9 in bean fields planted at different dates, 2008–2009

Sampling time	V3			R6-7			R9		
Factor levels	DI	DS	DX	DI	DS	DX	DI	DS	DX
May 2nd week	61.0[a]	3.2	43.5	70.4	3.6	54.7	61.7	2.7	44.2
May 3–4th week	49.9	2.6	34.6	63.6	3.0	45.6	52.8	2.1	35.4
Jun 1–2nd week	43.3	1.9	26.5	63.7	3.3	48.6	55.7	2.2	36.7
Jun 3rd week	17.9	0.7	9.2	47.5	2.5	35.4	48.8	1.7	29.2
May 2nd week	90.6[b]	–	54.5	99.8	–	79.0	91.7	–	56.1
May 3–4th week	68.8	–	35.7	94.3	–	59.2	75.1	–	37.3
Jun 1–2nd week	54.1	–	21.2	94.5	–	65.9	81.1	–	39.9
Jun 3rd week	9.8	–	2.6	63.4	–	37.3	66.4	–	25.7

[a] LSD between arcsine-transformed means of disease incidence and index and the means of disease severity within stage and within date were 12.6 and 16.6 for DI, 0.6 and 0.8 for DS, 9.6 and 12.8 for DX, respectively

[b] Back-transformed means

Urea usage

The common bean fields studied were categorized into the three classes with respect to urea usage as follows: 0 (13.1%), 1–50 (20.5%), and 50–500 kg/ha (66.4%; Table 1). The level of urea applied to the bean field significantly affected FRR incidence, severity and index over sampling time (Table 2). At V3, mean FRR severity was significantly greater for fields fertilized with 50 to 500 kg/ha of urea than for those that were non-fertilized (Table 14). Urea usage was positively correlated ($P<0.05$) with FRR variables at V3 (Table 10).

Weed density

The number of the fields at different levels of weed density changed with sampling date. A density of 1–15 weeds per quadrat was detected in the majority of bean fields surveyed as follows: 56.6% at V3, 75.4% at R6-7 and 66.4% at R9 (Table 1). Weed density had a significant effect only on FRR index (Table 2). Mean FRR index at R6-7 was significantly greater for the densest level of weeds (>16 weed/quadrat) than at the weed-free level (Table 15). Weed density was positively correlated ($P<0.05$) with FRR variables over the sampling dates (Table 10). The status of

Table 12 Incidence (DI), severity (DS) and index (DX) of Fusarium root rot assessed from growth stages V3 to R9 in bean fields planted at different depths, 2008–2009

Sampling time	V3			R6-7			R9		
Factor levels	DI	DS	DX	DI	DS	DX	DI	DS	DX
0–5 cm	32.9[a]	1.2	16.4	52.0	2.3	35.2	39.4	1.3	22.4
5–10 cm	40.5	2.0	25.7	59.5	3.1	44.9	58.4	2.3	38.4
10–22 cm	55.5	3.1	43.2	72.5	3.9	58.2	66.5	2.9	48.3
0–5 cm	32.4[b]	–	8.2	73.4	–	36.9	45.5	–	15.2
5–10 cm	47.9	–	20.0	88.1	–	57.6	86.2	–	43.4
10–22 cm	80.7	–	53.8	100.0	–	85.8	97.5	–	65.2

[a] LSD between arcsine-transformed means of disease incidence and index and the means of disease severity within stage and within depth were 9.6 and 15.0 for DI, 0.4 and 0.8 for DS, 7.4 and 11.4 for DX, respectively

[b] Back-transformed means

Table 13 Effect of the previous crop on incidence (DI), severity (DS) and index (DX) of Fusarium root rot assessed from growth stages V3 to R9 in bean fields, 2008–2009

Sampling time	V3			R6-7			R9		
Factor levels	DI	DS	DX	DI	DS	DX	DI	DS	DX
Alfalfa	38.3[a]	1.8	24.7	58.6	2.7	40.6	47.0	1.8	30.3
Barley	44.5	2.0	29.5	52.2	3.1	37.5	59.0	2.4	40.7
Bean	52.2	2.8	37.9	67.7	3.4	50.5	65.9	2.5	42.3
Maize	30.8	1.8	22.3	47.5	2.5	34.6	32.7	1.1	19.9
Potato	45.8	2.0	30.0	77.5	3.5	58.9	43.3	2.1	31.3
Tomato	46.0	2.0	25.6	67.7	3.6	57.6	70.1	2.8	47.2
Wheat	43.4	2.0	29.1	58.1	2.9	42.9	65.4	2.5	42.9
Alfalfa	43.2[b]	–	18.5	86.5	–	48.1	62.3	–	27.6
Barley	56.7	–	26.2	73.8	–	41.5	87.3	–	48.4
Bean	73.8	–	42.4	98.5	–	70.1	96.9	–	51.9
Maize	28.5	–	15.1	63.4	–	35.7	32.0	–	12.0
Potato	59.6	–	27.1	96.7	–	87.1	54.1	–	29.4
Tomato	60.1	–	19.8	98.5	–	84.7	99.7	–	62.8
Wheat	54.3	–	25.5	85.6	–	53.2	96.4	–	53.2

[a] LSD between arcsine-transformed means of disease incidence and index and the means of disease severity within stage and crop were 20.8 and 22.6 for DI, 1.0 and 1.2 for DS, 16.0 and 17.4 for DX, respectively

[b] Back-transformed means

weed density at pod maturity significantly affected on the yield factors examined (Table 4). Mean numbers of pods and seeds per plant in the densest weed populations were lower by nearly half of the corresponding values of the weed-free fields (Table 6).

Discussion

Much of our knowledge on the interactions of agronomic practices with FRR in beans is based on experiments performed on a small plot scale in individual fields, with experimental variables being precisely controlled. These valuable findings can benefit from large-scale studies, which allow a systematic understanding of the regional heterogeneity in environmental conditions that influence the interactions of agronomic operations with FRR and subsequent disease management outcomes. Even though surveying commercial fields suffers from the high variation of complicating variable effects (Fernandez et al. 2009), it is still useful to examine the agroecosystem–disease interface on a regional basis, which is highly relevant to commercial production conditions. To meet this requirement,

Table 14 Effect of the urea usage on incidence (DI), severity (DS) and index (DX) of Fusarium root rot assessed from growth stages V3 to R9 in bean fields, 2008–2009

Sampling time	V3			R6-7			R9		
Factor levels	DI	DS	DX	DI	DS	DX	DI	DS	DX
0 kg/ha	38.8[a]	1.6	23.7	63.0	2.8	44.6	50.7	1.9	33.1
1–50 kg/ha	39.4	2.0	26.6	58.8	3.0	45.2	51.2	2.0	32.9
50–500 kg/ha	50.9	2.6	35.1	62.1	3.4	48.5	62.5	2.6	43.1
0 kg/ha	44.3[b]	–	17.0	93.5	–	57.0	70.5	–	32.8
1–50 kg/ha	45.5	–	21.4	86.9	–	58.3	71.6	–	32.4
50–500 kg/ha	71.0	–	36.7	92.3	–	65.7	92.8	–	53.6

[a] LSD between arcsine-transformed means of disease incidence and index and the means of disease severity within stage and within urea were 11.6 and 15.8 for DI, 0.6 and 0.8 for DS, 9.0 and 12.2 for DX, respectively

[b] Back-transformed means

Table 15 Effect of weed density on incidence (DI), severity (DS) and index (DX) of Fusarium root rot assessed from growth stages V3 to R9 in bean fields, 2008–2009

Sampling time	V3			R6-7			R9		
Factor levels	DI	DS	DX	DI	DS	DX	DI	DS	DX
0 Weed/Quadrate	46.2[a]	2.3	30.6	54.0	2.8	39.8	46.4	1.9	32.9
1–15 Weed/Quadrate	48.2	2.3	31.7	60.5	2.9	44.1	54.6	2.2	35.9
> 16 Weed/Quadrate	34.7	1.6	23.0	69.4	3.5	54.3	63.2	2.4	40.3
0 Weed/Quadrate	60.5[b]	–	28.1	77.6	–	46.4	61.2	–	32.4
1–15 Weed/Quadrate	65.0	–	30.1	89.8	–	55.8	78.8	–	38.3
> 16 Weed/Quadrate	35.9	–	16.0	99.5	–	78.2	93.8	–	47.5

[a] LSD between arcsine-transformed means of disease incidence and index and the means of disease severity within stage and within density were 14.0 and 16.8 for DI, 0.8 and 0.8 for DS, 10.8 and 13.0 for DX, respectively

[b] Back-transformed means

the present work examined the primary linkages between a number of FRR, yield and agronomic traits at different growth stages in commercial bean fields. The results suggested that a considerable part of the variability in the FRR levels observed among bean fields corresponded with the combinations of the agronomic factors (excluding initial drought practice) surveyed. Such macro-scale evaluations will assist in the wise selection of more relevant agronomic strategies for bean protection and production in future field experimentations at Zanjan and in regions with similar cropping and climatic conditions. A greater FRR index in 2009 than in 2008 may reflect the influence of climatic conditions that varied from year to year. The higher FRR levels that were usually detected at R6-7 compared to V3 may be attributed to a general increase in disease symptoms with time. Moreover, this new detailed information on changes in the impacts of agronomic factors on FRR-development over the growing season demonstrates that a single measurement in time is unlikely to give an accurate representation of FRR-agroecosystem interplay from planting to crop maturity. Although a number of FRR and agricultural factors had significant impacts on bean yield, weak correlations revealed that other agronomic and environmental factors, in particular soil properties, should be considered in future studies to stabilize and enhance bean production.

In the present study, no significant effect of bean class on FRR factors was detected at V3 or R6-7, but at R9 Red beans had the lowest FRR index and the highest level of yield factors compared to Pinto and White beans. Further investigation is required to determine the basis for the reduced disease index at pod maturity in the Red beans, which produced the highest yield.

Non-significant and significant effects of FRR incidence and severity, respectively, suggest that disease index could be a more reliable criterion for the evaluation of FRR in interaction with bean production factors than FRR incidence or severity. As expected, the correlations indicated that lower yields in the bean crops were associated with higher FRR incidence and severity. Furthermore, FRR incidence and severity appeared to be responsible for 19% and 16–17% of the variation in pods and seeds production, respectively, among the fields surveyed. This appears to be the first description of correlations between common bean yield components and FRR incidence and severity at large-scale commercial fields.

In this research, attempts were made to elucidate whether an initial drought affected FRR or decreased yield by predisposing the bean crop to water stress or increased yield through the expansion of the root system to obtain water. Earlier findings showed that water stress in the vegetative stage had no impact on seed yields (Walker and Hatfield 1979), while water stress at either flowering or pod-filling stages reduced bean yield (Boutraa and Sanders 2002; Nielsen and Nelson 1998). Lack of a significant effect of initial drought at V3 on FRR and yield components in this regional study suggest that this operation could be practiced in bean fields as usual in order to lower cropping costs. Of course, further study on impact of spring rainfalls on the interaction between this practice and bean production is required.

The presence or absence of FRR and the level of cultivar resistance to the disease influence the impact of sprinkler irrigation regimes, so that frequent irrigation (every 3–5 days) increased bean yield on Fusarium-infested soil, but not on Fusarium-free soil (Miller and Burke 1986). Due to the inconsistent effect of soil moisture level (at 50 and 60%) on bean yield, Silbernagel and Mills (1990) advised extending irrigation intervals to 8–10 days in subsoiled fields to reduce production costs. This regional survey detected no significant association between yield components and irrigation frequency at the R9 stage. However, FRR levels at R6-7 were significantly higher in the fields irrigated every 2–3 days than those irrigated every 4–9 days. Irrigation frequency also accounted for 17% of the observed variation in FRR severity at R6-7. The significant role of this factor on the mid-season development of FRR suggests that irrigations as close as 2–3 days not only increases the level of FRR at flowering and pod formation stages, but also increases cropping expenses without a significant increase in yield. Definitely, future studies should include evaluation of cultivar resistance, amount of irrigation water, soil texture and compaction which are known to affect the interaction of FRR with yield.

Increases in FRR levels at R6-7 and subsequent death of FRR-affected plants may have resulted in a considerable reduction in the number of fields at the highest plant density (8–17 plant/quadrat) as the growing season progressed. The highest level of FRR factors was associated with the densest number of bean plants at R9. Stress factors such as overlapping roots and foliage resulting in competition for light, nutrients and water, and moist canopies, which usually happen in highly dense plantings from flowering (R6) onwards, must have been suitable for FRR development. Silbernagel and Mills (1990) reported that a cultivar-disease interaction in snap beans dominated the effect of plant density on seed production, so that narrow row spacing increased the bean yield in FRR-resistant cultivars, but not in susceptible cultivars. In this study, the denser plant populations at R9 corresponded with the lower production of pods and seeds per plant. Economic bean production requires further study of plant density affecting yield.

It was previously shown that FRR on White beans was more severe at 21°C than at 14°C or 28°C, while bean growth and dry weight were higher at 28°C than at soil temperatures of 14°C or 21°C (Sippell and Hall 1982). Higher disease levels occurring at V3 when planting coincided with cooler and moister weather conditions in May than in June seem to confirm earlier reports that the most severe FRR in beans occurred in fields planted in cold and moist soils (Burke and Miller 1983). Non-significant or weak associations between planting date and FRR variables at R6-7 and R9 suggest that the impact of planting date on FRR development is more important at the early stages of bean growth and decreases as the growing season proceeds. Furthermore, 29% of variation in FRR severity at V3 was associated with planting-date. However, late plantings produced pod and seed numbers similar to the early plantings in this study. Although late planting in spring appeared to restrict the establishment of FRR on bean crops in Zanjan, the lack of increase in yield levels may be partially attributed to the effect of cold conditions early in the autumn, which were unfavorable for pod maturity in late seeded fields.

Deep seeding may promote crop establishment and performance because of the greater availability of moisture in the subsoil. However, it may increase predisposition to FRR due to a prolonged period to emergence (Abawi and Pastor Corrales 1990). Siddique and Loss (1999) reported that the yield of chickpea and faba bean was increased by deep seeding. Another field study showed that shallow seeding (at 2.5 cm depth) was the most effective method among the cultural practices tested (seeding and hilling depth, and fungicide use) to decrease the severity of bean root rot (Brien et al. 1991); however, the impacts of those practices on the disease incidence and yield were not determined. To our knowledge, there is no previous report on how strongly planting depth interacts with the components of bean yield and FRR on a regional scale. At the sampling dates examined, our large-scale survey demonstrated that shallower planting was associated with lower FRR and greater yield levels. Regression analyses showed that 28–49% of the variation in disease severity, 27–42% in disease index and 14–23% in disease incidence on beans studied over the sampling time could be explained by planting depth. These relatively strong relationships indicate the important impact of planting depth on FRR establishment which remained significant through to pod maturity stage (R9).

The results of this study supports the recommendation of Bruehl (1989) that crop rotation, which benefits weed and insect management, should be a major factor in an integrated root rot control program. According to earlier documents, growing beans after maize, wheat or barley (Abawi and Pastor Corrales 1990; Maloy and Burkholder 1959), alfalfa (Román-Avilés et al. 2003) reduced root rot severity and improved bean production. This regional study also showed that beans planted following maize had lower FRR levels at the growth stages examined, so it could be a better crop choice than the other crops surveyed to be grown before bean. Furthermore, the observation that beans grown following alfalfa, barley or wheat had similar disease and yield component values to bean mono-croppings needs to be further examined using longer cropping sequences. It has been reported that the application of nitrogen fertilizers nullifies benefits of carbonaceous material such as barley and wheat residue in the soil (Huber 1963). Accordingly, fertilization of most fields with urea observed here may have accounted for the non-significant differences in FRR and yield component values observed between bean-monocultures and rotations with alfalfa, barley and wheat, so the effect of cropping history merits further investigation.

Contrary to the advice of local experts who recommend application rates of 20–50 kg/ha urea (based on an intensive examination of field soils, unpublished data) in the bean fields, this fertilizer was overused in the majority (66.4%) in most of the fields studied. According to the REML analysis, fertilizing fields with 50 to 500 kg/ha urea resulted in a significant increase in FRR severity early in the growing season compared with no fertilization. Results also indicated that 21% of the variation in disease severity and 19% in disease index at V3 could be explained by the amount of urea applied to the field. It has been documented that the ammonium form of nitrogen fertilizers enhances FRR on bean, whereas the nitrate form decreases the disease symptoms (Abawi and Pastor Corrales 1990; Huber and Watson 1970). The findings of this study indicate that the level of urea (ammoniacal-N-fertilizer) usage was positively linked not only to FRR severity, but also to FRR incidence and index at V3. In addition, there was no association between bean yield and urea usage in the fields. Further research could identify an appropriate nitrate fertilizer to reduce FRR and improve bean productivity.

Weed management by bean growers may have changed the number of the fields at specific weed densities over the sampling period; however, weeds were successfully controlled in only a small proportion of the fields surveyed. Based on information obtained from farmers, pre-planting control of weeds with Trifluralin and then hand-weeding were widely applied in Zanjan. The results determined that differences in weed density accounts for 12–21% of the variation in FRR index, 7–19% in FRR severity, 8–14% in FRR incidence, and 9–10% of the yield variation among the fields over the sampling time. These correlations along with the significant effects of this factor on mid-season FRR index and on bean yield suggests that weed control should be considered in comprehensive agronomic programs to increase production in Zanjan and to be as important as shallow seeding.

To our knowledge, this is the first report to establish the associations between agronomic, FRR and yield variables in commercial bean fields. To more clearly demonstrate relationships between these characteristics, field assessments were made at multiple times. Based on correlations, the three more effective agronomic practices influencing FRR were ordered as follows: planting depth, plant and weed density for FRR incidence, planting depth, date, and urea usage for FRR severity, and planting depth, date and plant density for FRR index. Furthermore, FRR incidence often had slightly weaker relationships with the agronomic variables than FRR severity and index. The results also suggested that pod and seed production had weaker correlations with the agronomic variables compared to FRR incidence and severity, which in turn were influenced by some of the agronomic variables. In conclusion, FRR and weed control, and shallow planting combined with appropriate plant density and seeding date established relatively stronger associations with bean FRR and yield among the factors studied here.

Acknowledgements This study was supported by the grant from the Iranian Ministry of Agriculture, research project no. 2-47-16-87083. The authors thank Mr. S.S. Mousavi for his valuable statistical advice and Mr. M. Maleki for his technical assistance.

References

Abawi, G. S., & Pastor Corrales, M. A. (1990). *Root rots of beans in Latin America and Africa: Diagnosis, research methodologies, and management strategies*. Cali: Centro Internacional de Agricultura Tropical.

Abawi, G. S., & Widmer, T. L. (2000). Impact of soil health management practices on soilborne pathogens, nematodes and root diseases of vegetable crops. *Applied Soil Ecology, 15*, 37–47.

Anonymous. (2005). *Agricultural production report in 2004*. Tehran: The Iranian Ministry of Agriculture.

Boutraa, T., & Sanders, F. E. (2002). Influence of water stress on grain yield and vegetative growth of two cultivars of bean (*Phaseolus vulgaris* L.). *Journal of Agronomy and Crop Science, 187*, 251–257.

Brien, R. G. O., Hare, P. J. O., & Glass, R. J. (1991). Cultural practices in the control of bean root rot. *Australian Journal of Experimental Agriculture, 31*, 551–555.

Bruehl, G. W. (1989). Integrated control of soilborne plant pathogens: an overview. *Canadian Journal of Plant Pathology, 11*, 153–157.

Burke, D. W., & Miller, D. E. (1983). Control of Fusarium root rot with resistant beans and cultural management. *Plant Disease, 67*, 1312–1317.

Deibert, E. J. (1995). Dry bean production with various tillage and residue management systems. *Soil and Tillage Research, 36*, 97–109.

Fernandez, M. R., Zentner, R. P., DePauw, R. M., Gehl, D., & Stevenson, F. C. (2007). Impacts of crop production factors on Fusarium head blight in barley in eastern Saskatchewan. *Crop Science, 47*, 1574–1584.

Fernandez, M. R., Zentner, R. P., Basnyat, P., Gehl, D., Selles, F., & Huber, D. (2009). Glyphosate associations with cereal diseases caused by *Fusarium* spp. in the Canadian Prairies. *European Journal of Agronomy, 31*, 133–143.

Fininsa, C., & Yuen, J. (2001). Association of maize rust and leaf blight epidemics with cropping systems in Hararghe highlands, eastern Ethiopia. *Crop Protection, 20*, 669–678.

Harveson, R. M., Smith, J. A., & Stroup, W. W. (2005). Improving root health and yield of dry beans in the Nebraska Panhandle with a new technique for reducing soil compaction. *Plant Disease, 89*, 279–284.

Huber, D. M. (1963). Investigations on root rot of beans caused by *Fusarium solani* f. *phaseoli*. Ph.D. Thesis, Michigan State University, USA.

Huber, D. M., & Watson, R. D. (1970). Effect of organic amendment on soil-borne plant pathogens. *Phytopathology, 60*, 22–26.

Kraft, J. M., Burke, D. W., & Haglund, W. A. (1981). *Fusarium* diseases of beans, peas, and lentils. In P. E. Nelson, T. A. Toussoun, & R. J. Cook (Eds.), *Fusarium: Diseases, biology, and taxonomy* (pp. 142–156). University Park: Pennsylvania State University.

Maloy, O. C., & Burkholder, W. H. (1959). Some effects of crop rotation on *Fusarium* root rot of bean. *Phytopathology, 49*, 583–587.

McDonald, A. J., Riha, S. J., & Mohler, C. L. (2004). Mining the record: historical evidence for climatic influences on maize–*Abutilon theophrasti* competition. *Weed Research, 44*, 439–445.

Mila, A. L., Carriquiry, A. L., Zhao, J., & Yang, X. B. (2003). Impact of management practices on prevalence of soybean Sclerotinia stem rot in the north-central United States and on farmers' decisions under uncertainty. *Plant Disease, 87*, 1048–1058.

Miller, D. E., & Burke, D. W. (1986). Reduction of Fusarium root rot and Sclerotinia wilt of beans with irrigation, tillage and bean genotypes. *Plant Disease, 70*, 163–166.

Moeini, M. R., & Ahmadi-Nejad, A. (1998). Assessment of common bean diseases in Zanjan province. In: *Proceedings of the 13th Iranian Plant Protection Congress*. Karaj, Iran: Plant Protection Research Institute.

Naseri, B. (2008). Root rot of common bean in Zanjan, Iran: major pathogens and yield loss estimates. *Australasian Plant Pathology, 37*, 546–551.

Nielsen, D. C., & Nelson, N. O. (1998). Black bean sensitivity to water stress at various growth stages. *Crop Science, 38*, 422–427.

Payne, R. W., Baird, D. B., Cherry, M., Gilmoure, A. R., Harding, S. A., et al. (2002). *GenStat Release 6.1*. Oxford: Rothamsted Experimental Station.

Rodríguez, E., García, P. A., García Garrido, J. M., & Campos, M. (2008). Agricultural factors affecting Verticillium wilt in olive orchards in Spain. *European Journal of Plant Pathology, 122*, 287–295.

Román-Avilés, B., Snapp, S. S., Kelly, J. D., & Kirk, W. W. (2003). Fusarium root rot of common beans. Extension bulletin E2876, Michigan State University, USA.

Sahile, S., Ahmedc, S., Fininsa, C., Abang, M. M., & Sakhuja, P. K. (2008). Survey of chocolate spot (*Botrytis fabae*) disease of faba bean (*Vicia faba* L.) and assessment of factors influencing disease epidemics in northern Ethiopia. *Crop Protection, 27*, 1457–1463.

Siddique, K. H. M., & Loss, S. P. (1999). Studies on sowing depth for chickpea (*Cicer arietinum* L.), faba bean (*Vicia faba* L.) and lentil (*Lens culinaris* Medik), in a Mediterranean-type environment of south-western Australia. *Journal of Agronomy and Crop Science, 182*, 105–112.

Silbernagel, M. J., & Mills, L. J. (1990). Genetic and cultural control of Fusarium root rot in bush snap beans. *Plant Disease, 74*, 61–66.

Sippell, D. W., & Hall, R. (1982). Effects of pathogen species, inoculum concentration, temperature, and soil moisture on bean root rot and plant growth. *Canadian Journal of Plant Pathology, 4*, 1–7.

Van Schoonhoven, A., & Pastor-Corrales, M. A. (1987). *Standard system for the evaluation of bean germplasm*. Cali: Centro Internacional de Agricultura Tropical.

Walker, G. K., & Hatfield, J. L. (1979). Test of the stress-degree-day concept using multiple planting dates of red kidney beans. *Agronomy Journal, 71*, 967–971.

Williams, M. M., Davis, A. S., Rabaey, T. L., & Boerboom, C. M. (2009). Linkages among agronomic, environmental and weed management characteristics in North American sweet corn. *Field Crops Research, 113*, 161–169.

Workneh, F., Tylka, G. L., Yang, X. B., Faghihi, J., & Ferris, J. M. (1999). Regional assessment of soybean brown stem rot, *Phytophthora sojae*, and *Heterodera glycines* using area-frame sampling: Prevalence and effects of tillage. *Phytopathology, 89*, 204–211.

Zanjan Meteorological Office. (2009). Annual weather reports for 2008–2009. http://www.zanjanmet.ir/. (accessed October 2009).

Zewde, T., Fininsa, C., Sakhuja, P. K., & Seid, A. (2007). Association of white rot (*Sclerotium cepivorum*) of garlic with environmental factors and cultural practices in the North Shewa highlands of Ethiopia. *Crop Protection, 26*, 1566–1573.