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Temporal progression of bean common bacterial blight (*Xanthomonas campestris* pv. *phaseoli*) in sole and intercropping systems

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Abstract

The effects of four planting patterns of bean (*Phaseolus vulgaris*) (bean only, maize–bean (MB), sorghum–bean (SB), and maize–bean–sorghum (MBS)) and four cropping systems (sole cropping, row, mixed, and broadcast intercropping) on the temporal epidemics of bean common bacterial blight (CBB) caused by *Xanthomonas campestris* pv. *phaseoli* were studied. The experiments were conducted during two consecutive spring and summer seasons in 1999 and 2000 in replicated field experiments. The Gompertz model described disease progress curves better than the logistic model. Intercropping delayed epidemic onset, lowered disease incidence and severity, and reduced the disease progress rate. The type of cropping system and planting pattern affected CBB incidence and severity at initial, final and overall assessments and also affected the rate of disease development. Statistical significance of treatment interactions based on disease assessments was found for incidence in all four experiments and for severity in three experiments. A slower disease progress rate and lower incidence and severity occurred on beans planted with maize or sorghum in row, mixed and broadcast intercropping than on bean planted alone. Incidence was reduced 36% and severity 20% in intercropping compared to sole cropping. The built-in disease delay and the slowing of the disease progress rate could provide protection for beans from severe CBB epidemics in intercropped systems. Variation between years appeared to be related to relative humidity (RH).

Introduction

Common bacterial blight (CBB) of common bean (*Phaseolus vulgaris* L.) caused by *Xanthomonas campestris* pv. *phaseoli* (Erw. Smith) Dowson is a major constraint of bean production in tropical and subtropical regions (Yoshii, 1980; Saettler, 1989). The disease is widely spread throughout Africa's major bean growing areas (Allen et al., 1989; Trutmann and Graf, 1993; Habtu et al., 1996). Various cropping systems and practices influence CBB occurrence and epidemics under field conditions (Fininsa and Yuen, 2001).

Intercropping, the simultaneous planting of more than one crop in the same area, is an important feature of cropping systems in the tropics. Common bean is commonly cultivated in Africa and Latin America under intercropping for a variety of socioeconomic and production reasons (Willey, 1979; Francis, 1986; Fininsa, 1997). Although these reasons are not explicitly clear to growers, benefits must be obvious since these systems persist. The system reduces, to various extents, disease incidence (Van Rheenen et al., 1981; Moreno and Mora, 1984; Sharaiha et al., 1989) and disease progress (Boudreau and Mundt, 1992; Boudreau, 1993; Fininsa, 1996; Theunissen and Schelling, 1996). Intercropping as a component of disease management may promote natural regulating mechanisms, such as those found in natural plant communities (Murdoch, 1975; Dinoor and Eshed, 1984; Knops et al., 1999), to maintain pathogen populations below the damage threshold. An intercropping effect, in an epidemiological context, may be defined as a change in disease intensity, disease progress rate or disease spread when a host species is grown in association in time and space with one or more different plant species compared with sole cropping of the host species.

Different cropping systems and planting patterns could influence disease development (progression) and the rate of disease progress. Characterisation of the temporal dynamics of disease incidence and severity is of fundamental importance in epidemiology when attempting to describe and understand the development of diseases, evaluate treatments and compare epidemics (Zadoks and Van den Bosch, 1994; Madden and Hughes, 1995). Intercropping may slow disease progress compared to sole cropping. Data on the temporal development of diseases in an intercropping system under different planting patterns are needed to use the system as a component in strategies to manage disease such as for CBB. However, very few empirical studies have been made to characterise, quantify, model and compare temporal disease progression in an intercropping system. Such information contributes to our understanding of the effects of intercropping, epidemiological dynamics and underlying mechanisms for disease development in mixtures of species.

The objectives of this study were to (i) quantify and characterise the temporal progress of CBB on bean in intercropped and sole plots under field conditions, and (ii) compare the effects of different cropping systems and planting patterns on the temporal disease progression and rate, and area under the disease progress curve (AUDPC).

Materials and methods

Temporal epidemics of bean CBB in sole and intercropped plots were studied during the spring and summer cropping seasons in 1999 and 2000 in Ethiopia. The experiments were conducted at the Alemaya University (AU) experimental field station (9°26′N, 42°3′E, 1980 m.a.s.l, 790 mm annual rainfall and bimodal rainfall distribution pattern) eastern Hararghe, Oromia. As the spring and summer experiments were different, field plots are described separately.

Spring field plots

Plots (11 m × 11 m) were planted in a randomised complete block design (RCBD) with four treatments in two replications (this plot size primarily was used for studies on disease spread). Sole cropping (pure stand of bean) and three planting patterns in mixed intercropping (bean plants within associate crop(s) rows) were used. The CBB-susceptible bean cultivar, *Red Wolaita* was used. Maize (*Zea mays* L.), variety *Bukuri* and sorghum (*Sorghum bicolor* (L.) Moench), variety *ETS2752* (*white Wagare*) were the associate crops. These were obtained from AU Crops Improvement Research Program and are widely grown in sole and intercropping systems in the region of the experimental site. The planting patterns were maize–bean (MB), sorghum–bean (SB), and maize–bean–sorghum (MBS).

Maize and sorghum were hand sown on 13 April 1999 and 15 April 2000 immediately after the onset of the rainy season. The resulting seedlings were thinned to one plant per hill, 17 days after planting. Beans were sown at a rate of one seed per hill on 30 April 1999 and 8 May 2000. Rows were oriented in a north–south direction. In pure stands, bean had 0.4 m between rows and 0.1 m within-row spacing (≅33 bean plants m^{-2}). In MB and SB intercropping, inter-row spacing was 0.75 m and within row was 0.3 m for maize plants and 0.2 m for sorghum plants. In the MB planting pattern where the maize : bean ratio was 1 : 2 per row (11 bean plants m^{-2}), beans were planted within the maize rows with spacing of 0.1 m between maize or bean plants. Beans were also planted in a similar manner in the SB planting pattern, for a sorghum : bean ratio of 1 : 1 per row (8.3 bean plants m^{-2}). In the MBS planting pattern, within-row spacing between each associate plant was 0.1 m (maize : bean : sorghum ratio was 1 : 2 : 1, 8.3 bean plants m^{-2}). The spacing between plots was 1.3 m and between blocks was 2 m. Hoeing and hand weeding practices were used but no fertiliser or bactericides were applied.

Summer field plots

Plots (7 m × 3 m) were planted in a randomised split-plot design with three replications. The main plots (21 m × 3 m) were four cropping systems: recommended sole cropping (pure stand of component crops), row intercropping (beans rows between associated crop(s) rows), mixed intercropping (beans within associated crop(s) in rows) and broadcast intercropping (beans within associated crop(s) without definite row or spacing). The broadcast intercropping (BI) represented farmers' growing practice around the experimental site and the region. Four planting patterns formed the sub-plots in each main plot. Sole bean planting was used in sole cropping (SC) system. MB, SB and MBS planting patterns were used in the other three main plots. The same associate cultivars of the spring season were used.

Maize was hand sown, two seeds per hill, and sorghum at many seeds per hill on 2 May 1999 and 4 May 2000. Twenty-nine days after planting, the resulting seedlings were thinned to one plant per hill. Beans were sown at a rate of one seed per hill on 1 June 1999 and 1 July 2000 (rainfall began late and planting was delayed). In row intercropping (RI) in each planting pattern, there were two rows of bean between maize or sorghum rows. Both MB and SB planting patterns consisted of five rows of maize or sorghum, and eight of bean.

In MBS planting pattern, the rows of sorghum and maize alternated. The planting consisted of three rows of sorghum, two rows of maize and eight rows of bean. In all planting patterns, MB and SB inter-row spacing was 0.18 m while within-row spacing for maize was 0.3 and 0.2 m for sorghum and bean was as in sole cropping in the spring experiments. Mixed intercropping (MI) consisted of five rows of the associated crops. In this system, within-row and inter-row spacing and plant ratios were as in the spring plots. In broadcast intercropping, mean bean plant proportions in MB, MBS and SB planting patterns were 52%, 59% and 65%, respectively.

Spacing was 1.3 m between plots and 2 m between blocks. With maize and sorghum planting, 200 g plot^{-1} (=100 kg/ha) of diammomnium phosphate fertiliser was applied. Frequent hoeing and hand weeding practices were used as weed control. During the 1999 cropping season, there was an infestation of armyworm (*Spodoptera exempta* (Wlk.): Lepidoptera, Noctuidea) that lasted 40 days (1 May–10 June) during the early growth period of maize and sorghum. The crops were protected by spraying frequently with 2.3 g^{-1} Carbaryl (Sevin 85% WP) and 2.3 ml l^{-1} Malathion (50% EC) insecticides with a knapsack sprayer. The infestation reduced plant stand and replanting of maize and sorghum occurred on 19 May to replace missing plants. In the same year, the plots were irrigated to save the trials from severe drought. All experiments relied entirely on natural inoculum for CBB development.

Disease assessment

In both seasons and years, incidence of CBB (number of plant units visibly diseased) per plot and severity (leaf area diseased) were assessed at 7-day intervals. Both incidence and severity were assessed to determine if the planting patterns and cropping systems had a differential influence on the two measures of disease. In the 1999 spring season, incidence was assessed three times beginning 55 days after planting (DAP) while in 2000 it was assessed seven times beginning 38 DAP. In the summer seasons of both years, incidence was assessed seven times beginning 52 DAP in 1999 and 38 DAP in 2000. Severity was rated on 12 randomly selected diseased and tagged bean plants in each subplot (excluding the two outer rows) beginning 52 DAP in both years of summer seasons using standard scales of 1–9 (CIAT, 1987), where 1 represents no visible symptom and 9 represents disease covering more than 25% of the foliar tissue. In the 1999 spring season, severity was assessed at 55, 62 and 69 DAP and in the 2000 season at 74 and 81 DAP. The frequency and beginning of disease assessment differed due to seasonal differences in disease onset. The severity grades were converted into percentage severity index (PSI) for analysis:

$$\text{PSI} = \frac{\text{Sum of numerical ratings} \times 100}{\text{No. plants scored} \times \text{maximum score on scale}}.$$

Meteorological data

Meteorological data for both growing seasons were obtained from the AU weather station. The data included daily minimum temperature (°C) recorded at 09:00 and maximum temperature at 18:00 h for the previous 24 h period, relative humidity (%) at 12:00 h, and rainfall (mm). The distance between the weather station and the location of the experiments was about 1.5 km (spring experiment) and 50 m (summer experiment).

Disease progression analysis

Means of incidence and severity from each plot were analysed. A number of generalised linear models were fit to both incidences and severities after transforming them with either the logistic, $\ln[y/(1-y)]$ (Vanderplank, 1963) and the Gompertz, $-\ln[-\ln(y)]$ (Berger, 1981) transformations. Cropping system and planting pattern were used as categorical variables in all analyses. In the first analyses, DAP (time) was also used as a categorical variable, which gave analyses that can be regarded as either RCBD (for the spring experiment) or split-plot design (for the summer experiments). Since the effect of planting pattern in the summer season data was confounded with cropping system effects, only the effect of cropping system is presented here. Most models showed a strong effect of DAP ($P \leq 0.05$) entered as a categorical variable, and linear models were then fit to the data with cropping system and planting pattern included as categorical variables (as above) but with time as a continuous variable. Models were constructed to yield intercept and disease progress rate (r) for each treatment over all assessment dates. Plots of residuals were examined to determine homogeneity of variance and lack of fit. The coefficient of determination (R^2) estimated the proportion of the variation explained by the model and used to compare models for each planting pattern and cropping system in spring and summer experiments.

With analysis of variance (ANOVA), a significant main effect ($P \leq 0.05$) was found for disease severity assessed in the spring crops of 1999 and 2000. The interaction effects with disease assessments during epidemic time (DAPs) were not significant. In this case, to compare disease progression among planting patterns, the AUDPC was calculated. AUDPC was calculated from severity assessments using the formula:

$$\text{AUDPC} = \sum_{k=1}^{n-1} [0.5(\text{PSI}_k + \text{PSI}_{k+1})]\,[t_{k+1} - t_k]\,,$$

where PSI_k is the severity index in proportion at kth assessment, t_k the time of the kth assessment in days from the first assessment date, and n the total number of days disease was assessed. (Campbell and Madden, 1990). Because severity index (PSI_k) was expressed in proportion and time (t_k) in days, AUDPC here was expressed in proportion days. ANOVA was performed on the AUDPC values calculated from each planting pattern and plots.

Initial and final incidence and PSI values presented in tables are based on untransformed data. The data had a better fit to Gompertz model than to the logistic, and the parameter estimates and their standard error presented are based on the Gompertz model. Least significance difference was used for mean separation where appropriate. Both ANOVA and linear regression were performed using the SAS GLM Procedure (SAS Institute, 1993).

Results

Incidence vs planting pattern

The effect of planting pattern on incidence of CBB during spring seasons in both 1999 and 2000 was significant ($P = 0.0001$, $R^2 = 93.4\%$ in 1999 and 78.8% in 2000). In 1999, incidence of CBB on bean planted with maize, sorghum and maize–sorghum was consistently lower than on bean planted alone (Figure 1). Initial assessment of incidence at 55 DAP on bean planted alone was higher (35.4%) than on MB (6.1%), SB (8.5%) and MBS (12.9%). Similarly, final assessment of incidence varied significantly among the planting patterns ($P = 0.003$). It was lower in MB and MBS

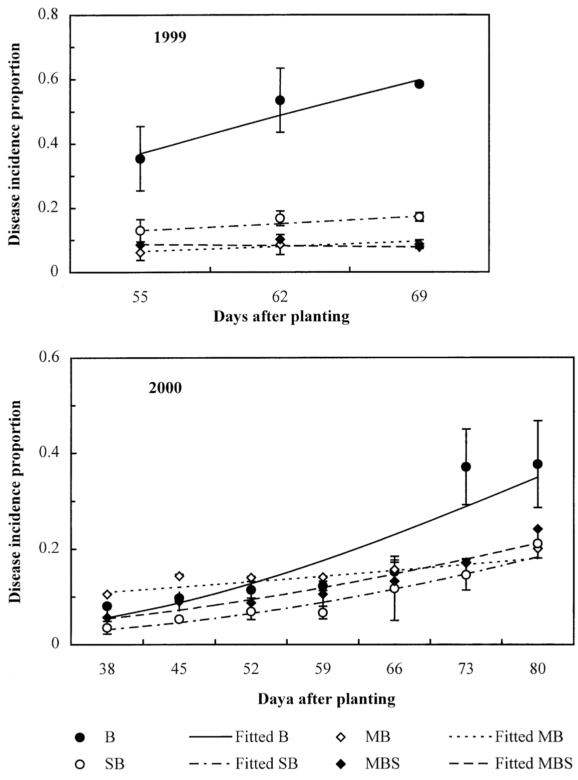

Figure 1. Progress curves of disease incidence of bean common bacterial blight (caused by *X. campestris* pv. *phaseoli*) in four planting patterns (MB = maize–bean, SB = sorghum–bean, MBS = maize–bean–sorghum, B = sole bean) in spring 1999 and 2000. MB, SB and MBS planting patterns were in mixed intercropping within rows. Data points represent mean values, the error bars represent standard errors and fitted curves are from the Gompertz model.

Table 1. Mean initial (Y_i) and final (Y_f) disease incidence, and parameter estimates for bean common bacterial blight (caused by *X. campestris* pv. *phaseoli*) in four planting patterns in spring seasons

Year	Planting pattern[1]	Y_i(%)[2]	Y_f(%)[3]	Intercept	SE[4] of intercept	Disease progress rate (gompit day^{-1})	SE[4] of rate	R^2(%)[5]	Significance (P)
1999	MB	6.1 b[6]	8.6 c	−1.61	0.99	0.011	0.015	88.8	0.11
	SB	12.9 b	17.1 b	−1.32	0.99	0.011	0.015	83.4	0.10
	MBS	8.5 b	7.8 c	−0.73	0.99	−0.003[7]	0.015	9.9	0.70
	B	35.4 a	58.4 a	−2.58	0.99	0.047	0.015	74.5	0.11
2000	MB	10.5 a	20.0 b	−1.02	0.18	0.006	0.003	79.8	0.0001
	SB	3.5 c	21.1 b	−1.89	0.18	0.017	0.003	78.8	0.0001
	MBS	5.7 bc	24.1 b	−1.64	0.18	0.015	0.003	89.6	0.0001
	B	8.0 ab	37.6 a	−1.97	0.18	0.024	0.003	78.1	0.0001

Parameter estimates are from a linear regression of − log (− log (disease incidence proportion)) on time (as days after planting, DAP). The intercept and slope represent the equation of the predicted line.
[1]MB, maize–bean; SB, sorghum–bean; MBS, maize–bean–sorghum; B, sole bean. MB, SB and MBS planting patterns were in mixed intercropping within rows.
[2]Initial disease incidence in 1999 was at 55 and in 2000 at 38 DAP.
[3]Final disease incidence in 1999 was at 69 and in 2000 at 80 DAP.
[4]SE, standard error of the mean.
[5]Coefficient of determination for goodness of fit to the Gompertz model.
[6]Values within a column and within a year followed by different letters are significantly different ($P \leq 0.05$).
[7]Negative disease progress rate calculated probably was due to defoliation of leaves from earlier diseased plants.

than in bean planted alone (Table 1). The interaction of planting patterns with incidence at three DAPs was also significant at ($P \leq 0.10$) which meant that disease incidence increased at different rates among the planting patterns.

In 2000, wave-like progress curves for disease incidence were observed, an indication that CBB was polycyclic as also shown in incidence of black rot of cabbage (Kocks et al., 1999). From 66 to 73 DAP (July 5–12), the incidence sharply increased in bean planted alone (Figure 1). This period had 5 days of rain (a total of 45.9 mm), the mean relative humidity (RH) was 67% and the maximum temperature was relatively high. These were favourable conditions for epidemics of CBB in pure stands of bean. Symptoms of CBB appear 5–7 days after natural infection. However, the incubation period can be influenced by inoculum concentration, temperature and RH (Goto, 1990). At 38 and 80 DAP (the first and last recorded disease incidence), there was a significant difference ($P < 0.05$) among planting patterns. At 80 DAP, incidence ranged from 20% in MB to 37.6% in bean planted alone. The interaction of planting patterns with incidence assessed at seven dates was significant ($P = 0.001$) and the disease progress rate in MB was slower (0.006 gompits day^{-1}) compared to bean planted alone (0.024 gompits day^{-1}) (Table 1). The disease progress rates in 2000 generally were slower than in 1999. For example, in 2000, the disease progress rate was slower by half for bean planted alone and for the MB intercrop.

Incidence vs cropping system

The effect of cropping system on incidence of CBB during the summer seasons was highly significant ($P = 0.0001$, $R^2 = 82.6$–86.1%). The progress curves for disease incidence in the cropping systems in both years had similar trends with observable differences between the years. Generally, in 1999, the progress was slow while in 2000 it was rapid (Figure 2).

In 1999, the progress curves for disease incidence in sole cropping were consistently high but were low for broadcast intercropping. Progress curves in row and mixed intercropping were intermediate. The curves had a trend of wave-like pattern with a sharp rise between 59 and 66 DAP (29 July–6 August), parallel trend between 66 and 87 DAP (6–27 August), and a second rise between 89 and 94 DAP (27 August–3 September). These trends were more conspicuous in sole cropping than in intercropping systems. The changes in the curves appear to be related to the weather conditions at the site during the experimental period. During the week of 29 July–6 August, maximum temperature at

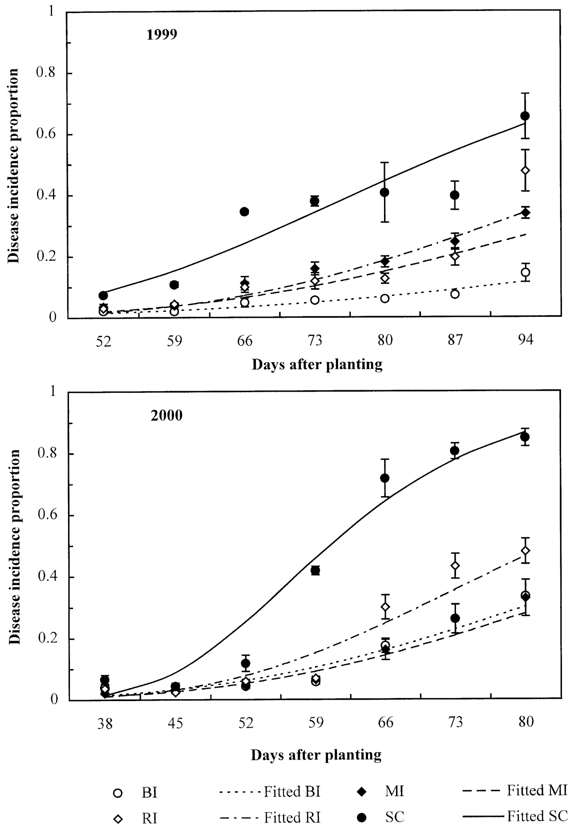

Figure 2. Progress curves of disease incidence of bean common bacterial blight (caused by *X. campestris* pv. *phaseoli*) in four cropping systems (BI = broadcast intercropping, MI = mixed intercropping within row, RI = row intercropping, SC = sole cropping) in summer 1999 and 2000. Data points represent mean values, the error bars represent standard errors and fitted curves are from the Gompertz model.

the site ranged from 23.5–25 °C and a total of 78 mm rainfall and the highest rainfall in a day (50 mm) for the season was recorded. High amounts of rain favour rapid progress of CBB in the field (Saettler, 1989). During three weeks of 6–27 August, 12 days had a maximum temperature less than 23.5 °C and the temperature increased from 28 August onward.

Incidence at initial assessment (52 DAP) was significantly different between sole and intercropping systems ($P = 0.004$). Low initial incidences (2.2–3.6%) were recorded in intercropping systems. Incidence at final assessment (94 DAP) was also significantly different among the cropping systems ($P < 0.05$). The lowest incidence (14.9%) at final assessment was recorded in broadcast intercropping (Table 2). The interaction of cropping system with incidence assessed at seven DAPs was significant ($P = 0.001$). CBB progressed at a slow rate (0.016 gompits day^{-1}) in broadcast intercropping and at a fast rate (0.040 gompits day^{-1}) in sole cropping.

In 2000, progress curves for disease incidence had typical characteristics of polycyclic diseases. Beginning from 52 DAP (20 August), conspicuous differences were observed among the progress curves for cropping systems (Figure 2). Incidence at initial assessment (38 DAP) was significantly different among the cropping systems ($P = 0.05$). The incidence ranged from 2.1% in mixed intercropping to 6.6% in sole cropping. Incidence at final assessment (80 DAP) varied between sole (84.9%) and intercropping systems (32.9–48%) ($P < 0.10$). The interaction of cropping system on incidence at seven DAPs was highly significant ($P = 0.0001$). The disease progress rate in sole cropping (0.081 gompits day^{-1}) was about three times faster than in mixed and broadcast, and two times faster than in row intercropping (Table 2). Generally, disease onset was about the same in both years but the rate of disease progress was faster in 2000 than in 1999. The progress rate in 2000 was 2.03 times faster for beans planted alone and 1.69 times faster for broadcast intercropping compared to these systems in 1999.

Severity vs planting pattern

The numbers of severity assessments carried out during spring seasons in both years were few. However, there were differences in some aspects of disease severity progress among the planting patterns. The effect of planting pattern on disease severity during the seasons in both years as indicated by ANOVA was significant ($P = 0.0001$ and $R^2 = 85.6\%$ in 1999; and $P = 0.01$ and $R^2 = 86.3\%$ in 2000). However, the interaction of planting pattern with severity assessed at three (1999) and two (2000) DAPs was not significant ($P > 0.10$). This means that disease severity increased in the different planting patterns about the same rate. In 1999, however, the AUDPC calculated for disease severity was different among the planting patterns with high AUDPC value for sole cropping and low for MB and MBS. In 2000, the AUDPCs were not significantly different (Figure 3).

Severity vs cropping system

The effect of cropping system on disease severity during summer seasons in both years was significant

Table 2. Mean initial (Y_i) and final (Y_f) disease incidence, and parameter estimates for bean common bacterial blight (caused by *X. campestris* pv. *phaseoli*) in four cropping systems in summer seasons

Year	Cropping system[1]	Y_i(%)[2]	Y_f(%)[3]	Intercept	SE[4] of intercept	Disease progress rate (gompit day^{-1})	SE[4] of rate	R^2(%)[5]	Significance (P)
1999	BI	2.2 b[6]	14.9 b	−2.27	0.18	0.016	0.002	75.9	0.0001
	MI	3.6 b	33.9 ab	−2.72	0.18	0.026	0.002	93.4	0.0001
	RI	3.1 b	47.6 a	−3.08	0.18	0.032	0.002	77.0	0.0001
	SC	7.4 a	65.4 a	−2.99	0.32	0.040	0.004	73.9	0.0001
2000	BI	4.0 a	33.5 b	−2.58	0.16	0.030	0.002	86.7	0.0001
	MI	2.1 b	32.9 b	−2.64	0.17	0.030	0.002	79.9	0.0001
	RI	3.7 a	48.0 b	−3.17	0.16	0.043	0.002	85.0	0.0001
	SC	6.6 a	84.9 a	−4.53	0.17	0.081	0.004	91.2	0.0001

Parameter estimates are from a linear regression of − log (− log (disease incidence proportion)) on time (as days after planting, DAP). The intercept and slope represent the equation of the predicted line.

[1]BI, broadcast intercropping; MI, mixed intercropping within row; RI, row intercropping; SC, sole cropping.

[2]Initial disease incidence in 1999 was at 52 and in 2000 at 38 DAP.

[3]Final disease incidence in 1999 was at 94 and in 2000 at 80 DAP.

[4]SE, standard error of the mean.

[5]Coefficient of determination for goodness of fit to Gompertz model.

[6]Values within a column and within a year followed by different letters are significantly different ($P \leq 0.05$).

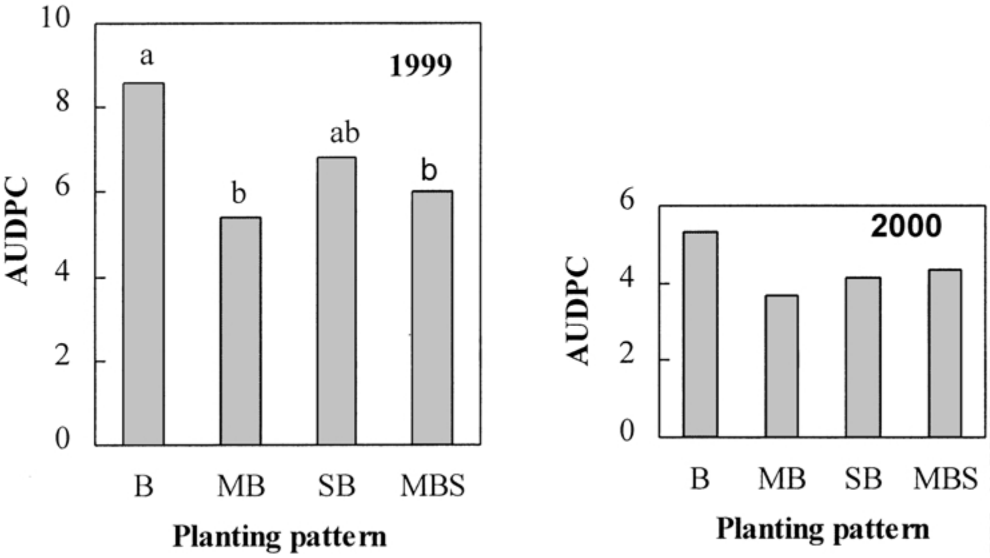

Figure 3. Area under the disease progress curves (AUDPC) for bean common bacterial blight (caused by *X. campestris* pv. *phaseoli*) in four planting patterns (MB = maize–bean, SB = sorghum–bean, MBS = maize–bean–sorghum, B = sole bean). MB, SB and MBS planting patterns were in mixed intercropping within rows. Values are means calculated from proportions of disease severity index assessed three (1999) and two (2000) times at 7-day intervals. Bars with different letters indicate significant difference ($P \leq 0.05$).

($P = 0.0004$ and $R^2 = 73\%$ in 1999; and $P = 0.0001$ and $R^2 = 92.9\%$ in 2000). The progress curves in the cropping systems had similar trends in both years with observable differences between the years (Figure 4). In 1999, severity at initial assessment (52 DAP) was not significantly different among the cropping systems ($P > 0.10$) while at final assessment (94 DAP) a significant difference between sole cropping (62.7%) and intercropping systems (41–47%) was found ($P = 0.10$). The interaction of the system with disease severity during the epidemic time (DAP) varied ($P = 0.06$). The disease progress rat in sole cropping

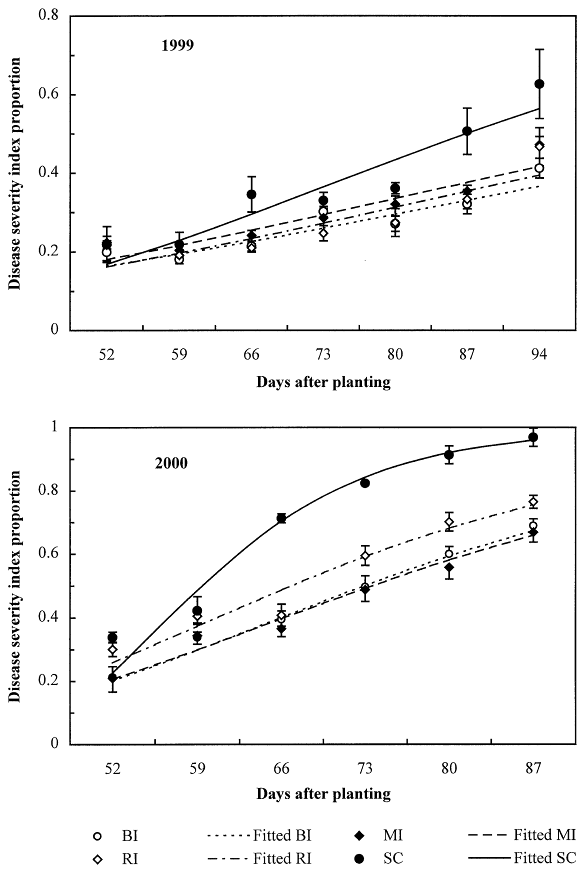

Figure 4. Progress curves of disease severity of bean common bacterial blight (caused by *X. campestris* pv. *phaseoli*) in four cropping systems (BI = broadcast intercropping, MI = mixed intercropping within row, RI = row intercropping, SC = sole cropping) in summer 1999 and 2000. Data points represent mean disease severity index values, the error bars represent standard errors and fitted curves are from the Gompertz model.

(0.027 gompits day^{-1}) was about two times faster than in broadcast intercropping (0.014 gompits day^{-1}) (Table 3).

In 2000, disease severity at both initial and final assessment (52 and 87 DAP) were significantly different among the systems ($P \leq 0.05$). At 52 DAP, severity in the system ranged from 21% in mixed and broadcast intercropping to 34% in sole cropping. At 87 DAP, the physiological maturing time of bean, most area of the diseased leaves (97%) in sole cropping were occupied by the disease while 24–32% of the area of diseased leaves in intercropping systems remained healthy (Table 3). The interaction of cropping system with epidemic time (DAP) was significant ($P = 0.0001$). The disease progress rate in sole cropping (0.104 gompits day^{-1}) was about three times faster than in mixed intercropping (0.038 gompits day^{-1}). In sole cropping, the disease covered wider parts of the leaf area than in intercropping systems. As for disease incidence, the disease progress rate for severity in 2000 was faster than in 1999. In 2000, disease progress rate in sole cropping was 3.85 times faster and in mixed intercropping 2.38 times than in 1999.

Discussion

In these four-field experiments, the planting patterns and cropping systems varied in their effect on CBB incidence, severity and disease progress rate in the spring and summer seasons. Intercropping systems reduced CBB temporal epidemics compared to sole cropping. The Gompertz model was a better descriptor of the natural epidemics in both bean-growing seasons than the logistic model.

Rapid progress of CBB and higher incidence and severity occurred on bean planted in sole cropping than on bean planted with maize or sorghum in row, mixed and broadcast intercropping. In intercropping systems, in any of the four seasons of CBB epidemic, incidence did not exceed 48% while it did reach up to 84% in sole cropping. Similarly, maximum severity on plants was 76% in intercropping while it reached about 97% in sole cropping. The disease-reducing effect of intercropping was greater on incidence than severity. This is because assessment of incidence considered the population of healthy and diseased bean plants while severity assessment was made only on samples of diseased plants. From the results, intercropping systems in effect delayed epidemic onset of CBB and slowed the disease progress rate. This disease delay and reduction of rate of disease progress could provide an escape for bean from severe epidemics of CBB. The system is functional because bean is a small plant and CBB has limited dispersal.

The results obtained are consistent with results of preliminary experiments on CBB at the experimental site during summer seasons (Fininsa, 1996), survey work in the region (Fininsa and Yuen, 2001) and field observations in Kenya (Van Rheenen et al., 1981). In earlier studies on other bean diseases such as bean rust (*Uromyces appendiculatus*) (Boudreau and Mundt, 1992; 1994; Fininsa, 1996; Fininsa and Yuen, 2001), reduced disease level in intercropping was found while variation across seasons and locations

Table 3. Mean initial (PSI_i) and final (PSI_f) disease severity index, and parameter estimates for bean common bacterial blight (caused by *X. campestris* pv. *phaseoli*) in four cropping systems in summer seasons

Year	Cropping system[1]	PSI_i[2]	PSI[3]	Intercept	SE[4] of intercept	Disease progress rate (gompit day^{-1})	SE[4] of rate	R^2(%)[5]	Significance (P)
1999	BI	20.0 a[6]	41.2 b	−1.32	0.14	0.014	0.001	85.5	0.0001
	MI	22.4 a	47.2 b	−1.37	0.14	0.016	0.001	96.0	0.001
	RI	21.8 a	46.6 b	−1.43	0.14	0.016	0.001	62.6	0.004
	SC	21.9 a	62.7 a	−1.98	0.25	0.027	0.003	73.9	0.0001
2000	BI	21.4 b	69.0 c	−2.55	0.23	0.040	0.003	95.2	0.0001
	MI	20.9 b	66.9 bc	−2.43	0.23	0.038	0.003	91.8	0.0001
	RI	30.1 a	76.5 b	−2.64	0.23	0.045	0.003	93.3	0.0001
	SC	33.9 a	96.9 a	−5.75	0.40	0.103	0.005	95.2	0.0001

Parameter estimates are from a linear regression of − log (− log (disease severity index proportion)) on time (as days after planting, DAP) and the intercept and slope represent the equation of the predicted line.
[1]BI, broadcast intercropping; MI, mixed intercropping within a row; RI, row intercropping; SC; sole cropping.
[2]Initial percent disease severity index in 1999 and in 2000 was at 52 DAP.
[3]Final percent disease severity index in 1999 was at 94 and in 2000 at 87 DAP.
[4]SE, standard error of the mean.
[5]Coefficient of determination for fit to Gompertz model.
[6]Values within a column and within a year followed by different letters are significantly different ($P \leq 0.10$).

Table 4. Summary of primary weather factors during the spring and summer seasons at Alemaya, Ethiopia

Season	Year	N[1]	Mean maximum temperature (°C)[2]	Mean RH (%)[2]	Rain days (>1 mm)	Total rainfall (mm)
Spring	1999	69	24.9 (1.7)	57.2 (7.8)	22	147.3
	2000	74	24.8 (1.5)	60.1 (7.8)	18	119.4
Summer	1999	94	23.6 (1.8)	75.8 (14.7)	33	365.5
	2000	80	23.5 (1.6)	67.6 (7.9)	31	307.3

[1]N is the number of days from planting to last date of disease assessment.
[2]The values in parenthesis indicate standard deviation of the mean.

was reported for angular leaf spot (*Phaeoisariopsis griseola*) (Boudreau, 1993).

Variation existed in CBB epidemics between 1999 and 2000 for both spring and summer experiments. The 1999 spring-season epidemics showed greater differences than in 2000. Although temperature and rainfall conditions of both spring seasons were similar, the 1999 spring (from the time of bean planting, 30 April to last date of disease assessment, 9 July) was less humid with a mean RH of 57%. In 2000, from the time of bean planting (8 May) to last date of disease assessment (20 July), a mean RH of 60% was recorded (Table 4). These relatively less humid conditions of 1999 could have increased the disease development. In the summer seasons higher disease occurred in 2000 than in 1999. Both seasons had similar patterns for rain days; rainfall and mean maximum temperature for the period from planting to last day of disease assessment (94 DAP in 1999 and 80 DAP in 2000). However, during this period the mean RH was 76% in 1999, while it was 68% in 2000. Therefore, given the differences in planting dates, the relatively less humid conditions of summer 2000 appear to have increased the disease. Association of CBB with low moisture conditions has been reported from studies conducted in Ethiopia (Habtu et al., 1996).

There are several possible mechanisms to explain why CBB is reduced in intercropping. The factors are a result from the system itself and include change in microclimate, reduced host density, induced resistance and competition. Each of the factors may have a minor role in affecting disease. In the system, because of shading by the associate crop, temperature is relatively lower which is known to delay development of CBB. Thus, the bacterial multiplication and movement within the plant cells could be reduced and lower the inoculum concentration and cause delayed disease onset. The associate host(s) (maize or sorghum) traps rain droplets and thus reduces the size of the droplet and the amount of rain the bean plant underneath is receiving. This, in turn, reduces the pathogen spread and contributes to slow the rate of infection.

The density of bean plants was 11 plants m^{-2} in MB mixed intercropping and 8.3 plants m^{-2} in SB. However, CBB in the MB planting pattern was lower in 1999 and slower in 2000 spring than in SB (Table 1). Thus, reduced bean density may not reduce CBB. However, the effect of plant density on disease in both sole cropping and species mixture is not well understood (Garrett and Mundt, 2000). Because of the presence of maize and or sorghum, the bean is under competition for resources. In intercropping, reduced bean size and leaf area indexes are known competition effects. The competition could also cause induced resistance, a reaction of the plant to the competition with the intercrop as suggested by Theunissen et al. (1995) for insect herbivore suppression on cabbage moth (*Mamestra brassicae*) and cabbage aphid (*Brevicoryne brassicae*) in cabbage–clover intercropping. Stress induced by competition could induce the plant to alter its physiology in such a way that it becomes less nutritious or more toxic to its pathogen. Boudreau and Mundt (1992), in their empirical study on bean rust in MB intercropping, reported greater maize competition effects in reducing the dispersal gradient of bean rust than maize effects of interference. However, more supportive experimental studies are required in this complex system of intercropping.

Variation in intensity of CBB and its progress rate among row, mixed and broadcast intercropping has to do with the level of microclimate change each system brings, the spatial arrangement of bean within each system and, possibly, to the degree of competition the bean plants encounter. In mixed and broadcast intercropping where the plants are under the associate crop(s) and not in separate rows, high competition and dispersal interference effects are likely. In row intercropping, where beans are planted in separate rows, close to the associate crop(s), competition, microclimate changes and interference effects would be less. In MB, SB, and MBS planting patterns, variation in CBB intensity could be related to the effects that the crops bring individually or in combination. The final effect on disease depends on the canopy and root structure and tillering capacity of the associate crops. For example, in MB intercropping, maize has a wider canopy and root structure and, hence, more effect on disease than sorghum in SB intercropping. However, the effect of these factors needs to be determined empirically and such experiments were beyond the scope of this particular study.

From these epidemiological experiments, a MB planting pattern in mixed intercropping in which greater disease reductions were found, could be used as a component to manage CBB in bean during both spring and summer bean-growing seasons in the Hararghe highlands and elsewhere with similar environmental settings. The system increases total productivity (Fininsa, 1997) and soil fertility (Aggarwal et al., 1992), and reduces bean insect herbivores (Risch, 1980; 1981). Intercropping could be used in management strategies for wind-born pathogens and for diseases that are favoured by high temperature, low RH and high rainfall. More data for host-pathogen systems in cereal–legume and cereal–vegetable intercrops, where the effect is likely, is required. If such wider research should prove to be useful, the system could be widely used by small farmers in the tropics and 'organic farmers' in temperate areas as a proactive component in integrated disease management schemes.

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