Analysing Crop-Loss in a Bean Rust Pathosystem. II. Severity - Damage Relationships

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Abstract

Field experiments were conducted from 1988 to 1993 at Ambo, Awassa and Debre Zeit, Ethiopia, to determine relationships of damage to crop growth and rust intensity in a bean rust pathosystem. A systemic fungicide (oxycarboxin) was applied at 5 spray frequencies to create differences in rust epidemic. The experiment was carried out in a production situation with low external inputs. Critical point models were examined based on rust severity and yield loss. Multiple regression models were developed for yield and yield loss by attempting to incorporate leaf area index, and rust incidence and severity in three canopy layers at one or more growth stages. Multiple regression models based on leaf area index and rust severity at growth stages R6 (flowering) and R7B (pod formation) fitted the data with R^2 values of 0.85. Addition of an incidence parameter did not improve the goodness of fit. Single point models developed at pod formation showed better fit than those developed at or prior to flowering. Models based on crop and disease assessments of the upper canopy layer produced good fit, but the goodness of fit was improved by including data from the middle canopy. For rust management purposes, crop and disease assessments from before flowering up to seed filling stages can be used. For survey purposes models based on assessments at the pod filling stage will be satisfactory.

Introduction

The impact of bean rust on yield of haricot bean is high even under low input conditions. However, yield loss varies with genotype, intensity of rust, location and season (Habtu et al. 1997). Farm operations are dynamic, cropping systems and use of external inputs may change overtime. Such dynamic changes will have an effect on the epidemics of diseases and subsequent impact on the damage to the crop. An economically sound disease management strategy requires an understanding of the relationships between production constraints, production situations and damage (Zadoks 1985). Several damage functions were proposed to estimate yield loss from disease intensity for cereals (James 1974, Burleigh et al. 1972, King 1976, Romig & Calpouzos 1970, Teng et al. 1979). In legumes, which often exhibit another mechanism of yield buildup (Gaunt 1987), information on such relationships is sparse. Yang et al. (1991) and Schneider et al. (1976) developed yield loss models for soybean rust (*Phakopsora pachyrhizi* Syd.) and cercospora leaf spot (*Cercospora cruenta* Sacc.) of cowpea (*Vigna unguiculata* L.). Savary and Zadoks (1992) developed a model of production constraints for varying production situations in groundnut. The latter model incorporated interaction between production situations (De Wit 1982) and damage. In bean rust, such information is absent.

Habtu and Zadoks (1995) and Habtu et al. (1997) described cross-sectional and longitudinal analyses (Zadoks 1978) of the effects of spray treatments on leaf area index and disease intensity per growth stage, and progress of crop growth and disease. In the present paper regression models for the relationships of damage with crop growth and disease intensity in a production situation with low external inputs are described.

Materials and Methods

Experiments were conducted at Ambo, Awassa and Debre Zeit from 1998 to 1993 in the experimental fields of the Institute of Agricultural Research at Debre Zeit (1850 m, *ca* 900 mm annual rainfall), Awassa (1750 m, 900 mm annual rainfall) and the Plant Protection Research Centre at Ambo (2150 m, *ca* 960 mm annual rainfall).

The experiments were conducted as randomized complete block design with six replications, in a split plot arrangement. For 1988 and 1989 experiments, the bean varieties 'Negro Mecentral', '6-R-395', 'Red Wolaita', 'Mexican 142' and 'Nazareth Small-03' were in main plots and fungicide treatments in sub-plots. In 1988, all entries were included but, in 1989, 'Red Wolaita' was omitted due to similarities in its rust reaction to 'Nazareth Small-03'. 'Negro Mecentral' was also omitted because of its high resistance to rust. In 1988, susceptible varieties were severely damaged by anthracnose, complicating the interpretation of results. Thus, in 1989 seeds were treated with benomyl (Habtu & Awgechew 1984) in an attempt to control anthracnose. In 1990, 1991 and 1993, two varieties - 'Mexican 142', susceptible (SUS), and '6-R-395', partially resistant (RES) - formed the main plots and five spray treatments the sub-plots. Seeds were sown in mid-June at Ambo and early July at Awassa and Debre Zeit. The experimental data at Debre Zeit in 1991 for RES were excluded from the analysis due to a severe infection by Bean Common Mosaic Virus (BCMV). Investigations in 1993 were confined to Ambo.

Standard agronomic practices were followed and no fertilizers were applied. The experimental sub-plots measured 4 x 4 m. One seed per hole was sown at 40 cm distance between the rows and 10 cm distance within a row. Each plot was surrounded by 3.2 m guard rows of wheat to reduce interplot interference.

Inoculation

Three weeks after emergence, each of the experimental plots was inoculated by spraying a urediniospore suspension (about 5 g urediniospore per 20 l of H_2O) containing a mixture of local isolates of bean rust collected from the respective locations.

Spray Treatments

Fungicide spraying began one week after inoculation. To produce epidemics of varying intensity in each variety, a systemic fungicide oxycarboxin (Bujulu & Lotasarwaki 1986, Lamamoto et al. 1971) at a rate of 0.1% a.i. was applied at intervals of 5 (treatment 4), 10 (treatment 3), 15 (treatment 2) and 20 days (treatment 1). A check (treatment 0) was left unsprayed to allow maximum development of bean rust.

Crop Assessment

Growth stages were determined at the dates of disease assessment, following Fernandez et al. (1986). At the first and last disease assessment dates, number of plants in the middle four rows of each plot was counted. Counts were converted to plant density (theoretically 25 plants m^{-2}). The leaf area of each plant selected for disease assessment was calculated using a pictorial key (Habtu et al. 1997). The leaf area index (LAI, leaf area per unit of soil area, $[L^2.L^{-2}]\tilde{N}$ [1], was determined at weekly intervals.

Disease Assessment

In 1988 and 1989 disease severity (1-9) was monitored weekly, commencing with the first spray. In 1991-93, from about 10 days after inoculation, assessment of incidence (number of infected leaves per plant), severity (percent leaf area infected), pustule density (number of pustules per leaf), and pustule size (1 = no visible symptoms, 2 = necrotic spots without sporulation, 3 = diameter of sporulating pustule < 300 μm, 4 = 300-500 μm, 5 = 500-800 μm and 6 = > 800 μm) were estimated (Stavely et al. 1983) at weekly intervals. Observations were made on 12 randomly selected and marked plants per plot, avoiding plot borders. Well developed green leaves randomly selected and representing the upper, middle and lower canopy layers were used for disease assessment. These tagged plants (non-destructive sampling) were used on each observation day.

Other diseases such as common bacterial blight (*Xanthomonas campestris* pv. *phaseoli* (Erw. Smith) Dowson) at Debre Zeit and anthracnose (*Colletotrichum lindemuthianum* (Sacc. and Magn.) Bri. and Cav. at Ambo, yellowing and dead tissue (mainly insect damage and slight necrosis) were assessed separately.

Yield Assessment

At the end of the growing season, seed yield (SY) in g plot^{-1} or m^{-2}, seed weight (SW) in mg seed^{-1}, number of pods plant^{-1} (PP), and number of seeds pod^{-1} (SP) of the four central rows were assessed. SY and SW were determined at 12% moisture after sun-drying threshed seeds for 5 days. PP and SP were counted at harvest. Losses in pods plant^{-1} (PL) and seed yield (YL) were estimated using the most frequently sprayed plots as references.

Regression Analysis

For the 1988 and 1989 experiments, the effects of been rust on seed yields of haricot bean were studied at Ambo and Awassa using critical point models. As Ambo and Awassa represent two different environments with different disease severities, the results are analysed separately. For experiments of 1990, 1991 and 1993, stepwise multiple regression analyses (Butt & Royle 1974, Teng 1980) were performed using yield and loss parameters as dependent variables and sets of crop and disease parameters as independent variables. Four variables were chosen to represent yield, pods per plant, seeds per pod, seed weight and seed yield. The independent variables were either rust severity or leaf area index, rust incidence, rust severity, pustule density, pustule size, the severity of other diseases and dead tissue. Each for the latter are assessed per canopy layer and at different growth stages (dates). A large number of combinations of independent variables were tested. Any independent variable that was not associated significantly with the dependent variable was discarded. The independent variables that accounted for the greatest amount of variation (high R^2) were retained. The remaining variables were regressed again and those with practical implications retained for analysis, interpretation of data and selection of models for future application. Analysis of variance and multiple regression analysis were performed using MSTAT and the SAS (1985) programme.

Results

Critical Point Models

At Ambo, in 1988, natural infection of bean by rust in sprayed and unsprayed plots produced mean rust severities ranging between 3 and 5 (Table 1). Differences among treatments in rust reaction were not significant probably due to delays in spraying. Though there were differences among treatments in seed yields, there were no consistent trends.

In 1989, there was a high incidence of rust and the three entries showed moderate to large rust reaction related to their levels of resistance. All spray schedules reduced disease reactions (Table 2), the least diseases occurring with the most frequent sprays. The trend was consistent for all the three entries. Differences in seed yield were also observed. Assigning an index of 100 to the dried seed yield at the lowest infection level, yield was reduced by 10-73% in 'Mexican 142', 8-67% in 'Nazareth Small-03' and 3-15% in '6-R-395'. The relationships between seed yields and rust reactions were highly significant

(Table 3), accounting for 83-96% of the variation in seed yields. Percent yield losses for every unit increase in disease reaction were 11.0% for 'Mexican 142', 9.7% for 'Nazareth Small-03' and 3.9% for '6-R-395'. Rust caused very large reductions in yields of 'Mexican 142' in both seasons, followed by 'Nazareth Small-03' and '6-R-395'. The R^2 values were also higher for 'Mexican 142' and 'Nazareth Small-03' and slightly less for '6-R-395'. For Awassa, in 1988, rust reactions were rated several times during the growing period but only disease reactions at maturity were used to relate to yields, as in Ambo. There were significant differences in rust reactions among entries and spraying with fungicide significantly reduced the rust reactions of 'Mexican 142', 'Nazareth Small-03', '6-R-395' and 'Red Wolaita' (Table 4) but not of 'Negro Mecentral', which is resistant to rust. The most frequent sprays consistently produced the least disease reactions and the largest yields (index =100%). Yield losses were small for 'Negro Mecentral' (0.3-4.1%) and '6-R-395' (0-5.3%), large for 'Nazareth Small-03' (19.2-27.6%) and intermediate for 'Mexican 142' (3.1-17.8%).

Table 1. Effect of bean rust on disease reaction and seed yield of haricot bean at Ambo, 1988.

Varieties	Spray interval (days)	Disease severity (1-9)	Seed yield (g/plot)	Index	Percent change in yield
Mexican 142	5	3	1800	100.0	0
	10	4	1830	101.7	+1.7
	15	5	1600	88.9	- 11.1
	20	5	1380	76.7	- 23.3
	Control	5	1450	80.6	- 19.4
Nazareth Small-03	5	3	1315	100.0	0
	10	4	1630	123.9	+ 23.9
	15	5	1240	94.3	- 5.7
	20	5	1660	126.0	+ 26.0
	Control	5	1110	84.4	- 15.6
6-R-395	5	4	1865	100.0	0
	10	4	2090	112.0	+12.0
	15	4	1920	103.0	+ 3.0
	20	5	1830	98.1	- 1.9
	Control	5	1390	74.5	- 25.5
Red Wolaita	5	3	1065	100.0	0
	10	4	1135	106.5	+6.5
	15	4	975	62.3	-37.7
	20	4	1070	91.5	- 8.5
	Control	5	900	84.5	- 15.5
Negro Mecentral	5	4	1100	100.0	0
	10	4	1315	120.0	+ 20.0
	15	4	1375	125.0	+ 25.0
	20	4	1130	103.0	+ 30.0
	Control	5	1250	114.0	+ 14.0

Table 2. Effect of bean rust on disease reaction and seed yield of haricot bean at Ambo, 1989.

Varieties	Spray interval (days)	Disease severity (1-9)	Seed yield (g/plot)	Index	Percent change in yield
Mexican 142	5	1.8	1267	100.0	0
	10	3.3	1144	90.3	-9. 7
	15	3.8	1108	87.5	- 12.5
	20	4.2	1071	84.5	- 15.5
	Control	6.8	341	26.9	- 73.1
Nazareth Small-03	5	1.6	1246	100.0	0
	10	3.2	1145	91.2	- 8.8
	15	4.0	1016	81.5	- 18.5
	20	4.6	1007	80.8	- 19.2
	Control	8.0	417	33.5	- 66.5
6R-395-08	5	1.4	1496	100.0	0
	10	2.8	1447	96.7	- 3.3
	15	3.2	1359	90.8	- 9.2
	20	3.8	1352	90.4	- 9.6
	Control	5.2	1271	85.0	- 15.0

Table 3. Coefficients of regressions of seed yield on rust reactions and percentage yield loss due to rust of entries in trials at Ambo, 1988 and 1989.

	1988			1989		
Entries	Regression coefficient	r value	Loss (%)	Regression coefficient	r value	Loss (%)
Mexican 142	- 203.3	0.30	8.1	- 191.0	0.90	11.0
Nazareth Small-03	- 127.3	0.08	6.5	-133.5	0.96	9.7
6-R-395	- 131.7	0.65	5.4	- 60.7	0.83	3.9
Red Wolaita	- 82.5	0.40	6.1	NT	NT	NT
Negro Mecentral	+20.0	0.01	0	NT	NT	NT

In 1989, the responses to application of fungicide were larger. Losses ranged between 4.1 and 23.3% in 'Mexican 142', 15.2 and 35.1% in 'Nazareth Small-03' and 8.3 and 13.6% in '6-R-395' (Table 5). In 1988, regressions of seed yield on the rust reactions for the individual entries (Table 6) showed that yields of 'Mexican 142' were reduced by 4.4% for each unit increase in disease reaction. For 'Nazareth Small-03', this was 7.8% for 'Red Wolaita' it was 6.3% and for '6-R-395', it was 3.9%. For 'Negro Mecentral' (resistant), there was no relationship between disease reaction and seed yield. In 1989, the yields of 'Mexican 142' decreased by 5.2% for each unit increase in disease reaction, by 5.5% for 'Nazareth Small-03' and by 2.6% for '6-R-395'.

Table 4. Effect of bean rust on disease reactions and seed yield of haricot bean at Awassa, 1988.

Entries	Spray interval (days)	Disease severity (1-9)	Seed yield (g/plot)	Index	Percent change in yield
Mexican 142	5	1.5	1339	100.0	0
	10	2.3	1297	96.9	-3.1
	15	3.8	1275	95.2	- 4.8
	20	4.5	1129	84.3	-15.7
	Control	5.3	1101	82.2	-17.8
Nazareth Small-03	5	1.7	1781	100.0	0
	10	2.8	1344	75.5	- 24.5
	15	4.0	1320	74.1	-25.0
	20	4.0	1440	80.8	- 19.2
	Control	5.5	1290	72.4	-27.6
6-R-395	5	2.5	2894	100.0	0
	10	1.7	2914	100.7	+ 0.7
	15	2.5	2741	94.7	- 5.3
	20	2.5	2902	100.3	+0.3
	Control	3.0	2743	94.7	- 5.3
Red Wolaita	5	1.5	1518	100.0	0
	10	2.8	1389	91.5	- 8.5
	15	2.7	1344	88.5	-11.5
	20	3.3	1239	81.6	-18.4
	Control	5.3	1117	73.6	-26.4
Negro Mecentral	5	1.5	2441	100.0	0
	10	1.5	2449	100.3	+0.3
	15	1.5	2341	95.9	-4.1
	20	1.7	2439	99.9	-0.1
	control	2.5	2434	99.7	-0.3

Table 5. Effect of bean rust on disease reaction and seed yield of haricot bean at Awassa in 1989.

Entries	Spray interval (days)	Disease severity (1-9)	Seed yield (g/plot)	Index	Percent change in yield
Mexican 142	5	1.0	1955	100.0	0
	10	1.6	1875	95.9	-4.1
	15	2.4	1550	79.3	-20.7
	20	3.2	1565	80.0	-20.0
	Control	5.4	1500	76.7	-23.3
Nazareth	5	2.0	1740	100.0	0
Small - 03	10	2.0	1760	101.1	+1.1
	15	3.8	1475	84.8	-15.2
	20	3.4	1360	78.2	-21.8
	Control	7.8	1130	64.9	-35.1
6-R-395	5	1.4	1990	100.0	0
	10	2.0	1825	91.7	-8.3
	15	2.0	1760	88.4	-11.6
	20	2.4	1825	91.7	-8.3
	Control	5.0	1720	86.4	-13.6

Table 6. Coefficients of regression for seed yield on rest reaction and percentage yield loss due to rust of entries in trials at Awassa, 1988 and 1989.

Entries	1988			1989		
	Regression coefficient	r value	Loss (%)	Regression coefficient	r value	Loss (%)
Mexican 142	-63.3	0.86	4.4	-101.2	0.68	5.2
Nazareth Small-03	-127.0	0.71	6.8	-102.7	0.85	5.5
6-R-395	-123.9	0.43	3.9	-51.7	0.50	2.6
Red Wolaita	-103.5	0.93	6.3	NT	NT	NT
Negro Mecentral	+22.4	0.00	0	NT	NT	NT

Multiple Regression Models

The independent variables selected and the equations computed for multiple regression analyses are given in Tables 7-10. Because of high genotype by treatment interaction, models in this paper are presented separately for susceptible (SUS) and partially resistant (RES) varieties.

Pods per plant (PP)

To develop the model we used the combined results of three years for SUS and two years for RES. For SUS we tested 14 combinations of which models using data of growth stage R7B or a combination of R6 and R7B were slightly better than models based on stage R6 (Table 7). Models with LAI and severity of rust were slightly better than those with LAI and rust incidence. All models resulted in R^2 values explaining 90% of the variation in PP. The best equations for PP contained two or three input variables at both R6 and R7B. When R6 and R7B were taken both, the combined use of LAI, rust incidence and severity of rust did not improve the R^2 value. For PP, middle and lower canopy layers were determinant since removal of the upper canopy layer did not change R^2. Generally, R^2 values were highest at stage R7B. For SUS the best models were models 1.1 - 1.4 (Table 8).

For RES, at R6 the use of incidence or severity variables did hardly affect R^2 values. When R6 and R7B were combined, models based on LAI and incidence showed a slight improvement. Models 2.1-2.4 (Table 8) were selected. Models 1.1, 1.2, 2.1 and 2.2 are single point models, with either R6 or R7B, while models 1.3, 1.4, 2.3, and 2.4 are two-point models.

Seed yield (SY)

For yield of SUS the best models were based on LAI and severity at two growth stages (Table 7), with R^2 values explaining85% of the variation. Generally, models based on R7B or on a combination of R6 and R7B resulted in R^2 values of 89% (models 3.2-3.4; Table 8). Inclusion of incidence did not affect the relationship, but exclusion of severity at upper canopy reduced R^2 by 1-3%. For SUS a combination of LAI and severity at growth stage R6 gave an acceptable model explaining 85% of the variation (model 3.1). For a similar combination at R7B R^2 increased by 4% (model 3.2). In these two cases addition of incidence variable did not improve the model. For RES the 14 models did not show substantial differences. For all practical purposes models 4.1-4.4 were considered satisfactory.

Pod loss (PL)

With SUS the best equations for PL were models 5.1-5.4 (Table 10) explaining 83% of the variation. Models using R6 (models 5.1 and 6.1) showed a 1-2% improvement over R7B models (models 5.2 and 6.2). For both SUS and RES exclusion of incidence did not change R^2 but exclusion of severity in the upper canopy resulted in lower R^2 values. For SUS, severity at R6 was more important than incidence. For RES inclusion of rust severity at lower canopy did not improve R^2 (Table 9).

Table 7. Multiple regression equations and coefficients of determination (R^2) values for pods per plant (PP) and seed yield (SY)[1] in bean rust

Independent variables					Dependent variables			
		Severity			PP		SY	
LAI	IN	UC	MC	LC	SUS	RES	SUS	RES
R6	R6	R6	R6	R6	0.91	0.92	0.87	0.89
R6	R6		R6	R6	0.91	0.92	0.85	0.89
R6	R6				0.90	0.92	0.85	0.89
R6		R6	R6	R6	0.91	0.92	0.87	0.89
R6			R6	R6	0.91	0.92	0.85	0.89
R7B	R7B	R7B	R7B		0.92	0.93	0.89	0.89
R7B	R7B				0.92	0.93	0.88	0.89
R7B		R7B	R7B		0.92	0.92	0.89	0.89
R6-R7B	R6-R7B				0.92	0.93	0.89	0.89
R6-R7B		R6-R7B	R6-R7B		R6	0.92	0.93	0.90
0.89								
R6-R7B		R6-R7B	R6-R7B			0.92	0.93	0.89
0.89								
R6-R7B	R6-R7B		R6-R7B			0.92	0.93	0.89
0.89								
R6-R7B	R6-R7B	R6-R7B	R6-R7B			0.92	0.93	0.89
0.89								
R6-R7B	R6-R7B	R6-R7B	R6-R7B		R6	0.92	0.94	0.90
0.89								

[1]*LAI=leaf area index; IN=rust incidence; RS=rust severity; UC=upper canopy layer, MC=middle canopy layer; LC=lower canopy layer; PP=pods plant^{-1}; SY=seed yield in g m^{-2}; SUS=susceptible, 'Mexican 142'; RES=partially resistant, '6-R-395'.*

Yield loss (YL)

For SUS, YL was best estimated by models including variables at both stages R6 and R7B (Table 9). Addition of incidence or subtraction of severity at lower canopy did not affect the outcome. The best models explained 86% of the variation (models 7.3 and 7.4, Table 10). These models showed a 1-4% improvement in R^2 over models for either R6 or R7B (models 7.1 and 7.3). Again, addition of incidence gave no improvement.

For RES the trend was similar to SUS. Models 8.1 and 8.2, which consider variables at either R6 or R7B, explained 73 and 74% of the variation. No information was lost by excluding incidence. Models 8.3 and 8.4, which consider R6 and R7B simultaneously, were marginally better. For RES the percent variation in yield loss explained by all 14 models was relatively low, in the range of 72-77%.

Discussion

Critical Point Models

Crop loss varied among entries, years and locations, which can be expected due to differences in disease resistance and variations in weather and their subsequent impact on rust initiation and development. Obviously, the relationships demonstrated are valid only within the limits of these experiments, but the more information of this sort that can be assembled, the greater will be the accuracy with which the yield losses due to rust and other diseases across environment can be assessed. In 1989, as other diseases were practically unimportant and rust severities correlated well with yield, rust was most likely responsible for observed crop losses relative to the yields of the most frequently sprayed plots.

Among other factors, final crop yields are influenced by the severities of the diseases that occur during crop growth, which are also related to the rates of disease progress. The apparent infection rate (van der Plank 1963) results presented here followed a critical point model. Critical point models estimate yield losses for any level of disease at a time when a specified level of disease is reached (James & Teng 1979). They assume that years, environments and varieties are typical in terms of duration and time of onset of disease and stability of infection rate. This may not be so under natural conditions; crop-loss experiments should examine the role of initial infection and its subsequent development in yield loss.

Moreover, more than a single disease can be present at any one time (for example, angular leaf spot and common bacterial blight at Awassa and anthracnose and ascochyta blight at Ambo) and their contribution to yield loss cannot be neglected in establishing prediction models. It is thus essential to collect more precise data to establish multiple point models by continuing field experiments, repeated both in time and space.

Multiple Regression Models

Models linking disease intensity (rust incidence or severity of rust) and crop growth (LAI) seem to be a realistic approach to crop loss studies (MacKenzie & King 1980). The relation between severity and yield is often disappointing (Waggoner & Berger 1987) because the effect of severity is different for early and late observations, or because defoliation is not included in severity assessment. In our model we tried to incorporate LAI, rust incidence and rust severity in three canopy layers at one or more growth stages in a multiple regression analysis. Two-point equations based on LAI and severity explained the relationship better than single point equations based on LAI and incidence or severity. Equations at later growth stages showed a better fit than at earlier growth stages. For bean varieties with indeterminate growth habit, the growth stages R5 or R6 might be a bit early to estimate yield or yield loss but for varieties with determinate growth R6 could be used. At Ambo the inoculum arrived early and the onset of an epidemic can be at the vegetative stage. Here, it is believed that equations at growth stage R6 will give a better estimate of yield or yield loss.

The results obtained here confirm those of others (Teng et al. 1979). An assessment at one critical growth stage may be adequate but a better fit can be obtained by using assessments at more growth stages. Although models based on the upper canopy layer were satisfactory, they were improved by including data from the middle canopy layer. The dynamics of yield

Table 8. Multiple regression equations, partial regression coefficients and coefficients of determination (R^2) for pods per plant (PP) and seed yield (SY)[1] in bean rust

			LAI		IN		RS					
							UC		MC		LC	
Model	Y	a[2]	R6	R7B	R6	R7B	R6	R7B	R6	R7B	R6	R^2
1.1	PPsus	19.6	0.13	-	-	-	0.01	-	0.001	-	-0.13	0.91
1.2	PPsus	14.8	-	1.86	-	-	-	-0.01	-	-0.02	-	0.92
1.3	PPsus	15.5	-0.47	2.03	-	-	0.05	-0.02	0.01	-0.01	-0.09	0.92
1.4	PPsus	15.8	-0.47	1.97	-0.01	-0.003	0.06	-0.02	-0.01	-0.008	-0.10	0.90
2.1	PPres	24.8	0.75	-	-	-	-0.07	-	-0.01	-	0.04	0.92
2.2	PPres	25.7	-	0.26	-	-	-	0.01	-	0.01	-	0.93
2.3	PPres	24.3	0.64	0.24	-	-	-0.07	0.01	-0.03	0.04	0.06	0.93
2.4	PPres	23.9	0.37	0.52	0.004	-0.07	-0.05	0.03	-0.04	0.04	0.06	0.94
3.1	SYsus	245	3.1	-	-	-	-1.30	-	0.28	-	0.93	0.85
3.2	SYsus	177	-	25.4	-	-	-	-0.51	-	0.06	-	0.89
3.3	SYsus	185	-4.69	27.9	-	-	-0.58	-0.50	0.44	0.003	1.43	0.92
3.4	SYsus	190	-5.24	27.3	0.49	-0.20	-0.28	-0.48	0.56	0.02	1.27	0.90
4.1	SYres	300	-5.37	-	-	-	0.81	-	-0.09	-	1.14	0.89
4.2	SYres	305	-	7.37	-	-	-	-0.26	-	0.36	-	0.89
4.3	SYres	307	3.79	-5.12	-	-	1.39	-0.51	-0.43	0.69	1.49	0.89
4.4	SYres	309	-5.88	-4.27	-0.69	0.15	1.36	-0.54	-0.43	0.67	1.51	0.89

[1]LAI=leaf area index; IN=rust incidence; RS=rust severity; UC=upper canopy; MC=middle canopy; LC=lower canopy; PP=number of pods plant^{-1}; SY=seed yield in g m^{-2}; SUS=susceptible, 'Mexican 142'; RES=partially resistant, '6-R-395'.
[2]a=intercept, other entries are partial regression coefficients, -=not relevant.
[3]R6=flowering stage; R7B=pod setting stage, second week; R^2=coefficient of determination, significant at $P<0.05$

buildup in legumes is unclear and it is not known which nodes contribute most to the final yield (Debouck 1991). The ability of a model to estimate yield and yield loss accurately is judged by its applicability under different environments (Zadoks & Schein 1979). Our models incorporated data covering a fairly wide range of growing conditions.

Farmers in Ethiopia use different varieties to suit their needs. The varieties vary not only in their susceptibility to bean rust but also in their growth habit and use. In view of the large differences between varieties, separate regression models should be developed for varieties representing defined resistance classes. More information is needed in this area.

Applications

Yield loss models could have several applications, be it in the area of planning, market development or rust management (Zadoks 1985). Under current Ethiopian conditions an important issue is when to assess crop and disease parameters to accurately estimate yield or yield loss. Yield and yield loss equations established at growth stages R6 and R7B are acceptable for application in practice. For extension specialists a fair estimate of yield or yield loss can be achieved by a single assessment at R7 (Models 3.2 and 4.2 for SY). For policy decisions, where yield loss estimates may be the objective, models 7.2 and 8.2 may be applied. For rust management purposes, crop and disease assessments starting at or before flowering (R5 and R6) will give a realistic estimate. The dates of field operations, especially sowing, vary from field to field even within one region. It is thus recommended that field visits coincide with the growth stages (R6-R7B) described above, where possible.

The magnitude of yield loss depends in part on the amount of inoculum arriving during the vegetative stage. A model which covers this aspect of epidemiology would explain yield and

Table 9. Multiple regression equations and coefficients of determination (R^2) values for pod loss (PL) and seed loss (YL)[1] in bean rust

Independent variables		Dependent variables						
		Severity			PL		YL	
LAI	IN	UC	MC	LC	SUS	RES	SUS	RES
R6	R6	R6	R6	R6	0.83	0.80	0.83	0.75
R6	R6		R6	R6	0.83	0.79	0.80	0.74
R6	R6				0.82	0.79	0.80	0.73
R6		R6	R6	R6	0.83	0.80	0.83	0.74
R6			R6	R6	0.83	0.79	0.80	0.73
R7B	R7B	R7B	R7B		0.85	0.82	0.85	0.73
R7B	R7B				0.85	0.82	0.85	0.72
R7B		R7B	R7B		0.85	0.79	0.85	0.73
R6-R7B	R6-R7B				0.86	0.82	0.85	0.73
R6-R7B		R6-R7B	R6-R7B	R6	0.86	0.80	0.86	0.76
R6-R7B	R6-R7B	R6-R7B			0.86	0.80	0.85	0.74
R6-R7B	R6-R7B	R6-R7B			0.86	0.83	0.85	0.74
R6-R7B	R6-R7B	R6-R7B	R6-R7B		0.86	0.83	0.86	0.76
R6-R7B	R6-R7B	R6-R7B	R6-R7B	R6	0.86	0.84	0.87	0.77

[1]LAI=leaf area index; IN=rust incidence; RS=rust severity; UC=upper canopy layer, MC=middle canopy layer; LC=lower canopy layer; PL=loss in pods plant^{-1}; YL=loss in seed yield in g m^{-2}; SUS=susceptible, 'Mexican 142'; RES=partially resistant, 6-R-39

yield loss fairly accurately, and thus help in the management of rust. Generally, the equations accounted for a fairly high proportion (74-92 %) of the variation. Part of the unexplained variance could be due to variables and interactions not included. Other diseases such as common bacterial blight (*Xanthomonas campestris* pv *phaseoli* (Erw. Smith) Dowson, anthracnose (*Colletotrichum lindemuthianum* (Sacc. and Magn) Bri. and Cav.) and ascochyta blight (*Phoma exigua* (Desm)), insect pests and dead tissue (necrosis by unknown causes) occur simultaneously with rust. Knowledge of the role of these diseases either independently or in a multiple pathosystem will further improve the accuracy of estimation of bean yield and yield loss. An understanding of this dynamic relationship will help us develop an acceptable disease management strategy. The study reported here emphasised seed yield and gave little attention to the effect of diseases on seed quality and straw weight which are important to the Ethiopian farmer, especially in areas where seed is produced for cash and straw for fodder.

Understandably, there is lack of information on the quantitative relationship of these factors. An over-all crop management strategy necessitates a better knowledge of these relationships.

Table 10. Multiple regression equations, partial regression coefficients and coefficients of determination (R^2) for pod loss (PL) and seed loss (YL)[1] in haricot bean.

			LAI		IN		RS					
							UC		MC		LC	
Model	Y	a[2]	R6	R7B	R6	R7B	R6	R7B	R6	R7B	R6	R2
5.1	PPLsus	5.9	-0.12	-	-	-	-0.004	-	-0.005	-	0.11	0.83
5.2	PPLsus	11.0	-	-1.94	-	-	-	0.01	-	-0.003	-	0.85
5.3	PPLsus	10.2	0.48	-2.11	-	-	0.04	0.02	-0.02	0.002	0.08	0.86
5.4	PPLsus	9.8	0.49	-2.03	0.01	0.01	-0.05	0.02	-0.02	0.001	0.08	0.86
6.1	PPLres	0.61	-0.75	-	-	-	0.07	-	0.01	-	-0.04	0.80
6.2	PPLres	0.28	-	-0.26	-	-	-	-0.01	-	-0.01	-	0.79
6.3	PPLres	1.07	-0.64	-0.24	-	-	0.07	-0.01	0.03	-0.03	-0.06	0.80
6.4	PPLres	1.48	-0.37	-0.52	-0.004	0.07	0.05	-0.03	0.04	-0.04	-0.06	0.84
7.1	SYLsus	54	-3.09	-	-	-	1.30	-	-0.28	-	-0.93	0.83
7.2	SYLsus	122	-	-25.3	-	-	-	0.51	-	-0.06	-	0.85
7.3	SYLsus	114	4.70	-27.9	-	-	0.58	0.50	-0.43	-0.00	-1.43	0.86
7.4	SYLsus	109	5.24	-27.3	-0.49	0.20	0.28	0.48	-0.56	-0.02	-1.27	0.87
8.1	SYLres	-10.3	7.21	-	-	-	-1.64	-	0.06	-	-1.13	0.74
8.2	SYLres	-1.2	-	3.29	-	-	-	0.07	-	-0.45	-	0.73
8.3	SYLres	-9.4	7.35	0.31	-	-	-2.15	0.40	0.53	-0.85	-1.66	0.76
8.4	SYLres	-10.5	11.4	-2.12	1.29	0.09	-2.18	0.37	0.56	-0.83	-1.68	0.77

[1]LAI=leaf area index; IN=rust incidence; RS=rust severity; UC=upper canopy layer, MC=middle canopy layer, LC=lower canopy layer, PL=loss in number of pods plant^{-1}; YL=loss in seed yield in g m^{-2}; SUS=susceptible, 'Mexican 142'; RES=partially resistant, '6-R-395'.
[2]a=intercept, other entries are partial regression coefficients; -=not relevant.
[3]R6=flowering stage, R7B=pod setting stage, second week, R^2=coefficient of determination, significant at $P<0.05$

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