PN-ABL-578
ISN 77841

Rwanda Farming Systems Research Program
Technical Paper Series

USAID Contract #696-0110

between

The University of Arkansas, Fayetteville
(International Agricultural Programs)

and

The Rwandan Ministry of Agriculture
Rwandan Institute for Agricultural Sciences (ISAR)

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on Farm Fields in the Buberuka
Highlands of Rwanda

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ANALYSIS OF FACTORS RELATED TO WHEAT YIELD ON FARM FIELDS IN THE BUBERUKA HIGHLANDS OF RWANDA

J.R. Burleigh, C.R. Yamoah, J.L. Regas, and Val J. Eylands[1]

ABSTRACT

The wheat (*Triticum aestivum* L.) improvement program in Rwanda has focused on disease resistance, but other factors, including site characteristics, may impact on cultivar performance. The objectives of this study were to identify on farm fields those factors related to wheat yield that may enhance the wheat improvement strategy. Soil samples from 25 fields in 1988 and 30 in 1989 were analyzed for chemical properties. Fields were characterized by slope, azimuth, irradiance and disease severity. Grain yield and yield components were regressed on soil and site characteristics and on disease development. Nitrogen and Al explained 35% of the variability in tiller and spike numbers for 1988 whereas slope and stripe rust severity comprised the best model for 1989. For combined seasons, N and Al, powdery mildew and stripe rust severities and field slope explained 55% of the variability in tiller and spike numbers. Tillers and spikes/m^2 also were correlated as a second degree polynomial with irradiance, and maximum numbers occurred at 28 MJ/m^2/day. Aluminum and N were significant variables for grains per spike in 1989, and their regression coefficients usually were not significantly different between seasons. Among most yield components their standard partial regression coefficients usually were greater than for other independent variables. Azimuth and slope were model components for grains/spike, kernel weight and grain yield. Responsiveness to N and tolerance to Al, therefore, are important selection criteria, and the continued search for resistance to *Puccinia striiformis* West. and *Erysiphe graminis* DC. f. sp. *tritici* E. Marchal is warranted. Yields could be improved by selecting lines that tiller well under high solar flux and testing early generations on sites representative of the region.

INTRODUCTION

Rwanda cultivates 4000 ha of wheat and has an active wheat improvement program in cooperation with CIMMYT (Centro Internacional de Majoramiento de Maiz y Trigo-Mexico). The program focus is on disease resistance, particularly resistance to stripe rust (caused by *Puccinia striiformis* West.). Lines emerging from the program (Rwerere, Muhonyore, Inkiga, Nsibu, Musama, Cyihure, Rugezi, Mbundi and Kalima) have good resistance to *P. striiformis*, but yields from multilocational sites on farm fields do not exceed yields of local cultivars that are susceptible to the pathogen (Paul et al., 1987). This brings into question the importance of resistances to stripe rust as the principal selection criterion for cultivar improvement. Visual observations suggest that disease might not be a major constraint to yield since severities of the principal pathogens (*P. striiformis*, *P. recondita* Rob. ex Desm. f. sp. *tritici* and *Erysiphe graminis* DC. f. sp. *tritici* E. Marchal) seldom exceeded 30% at soft dough (GS 83, Zadoks et al., 1974.)

In the Buberuka highlands, mean wheat yield on farm fields is 850 kg/ha (Paul et al., 1987) whereas on the Rwerere experiment station where cultivar selection is done, mean yield is 3000 kg/ha. Factors limiting yield on farm fields are unknown. Previous work (Paul et al., 1987) shows that farm yields were doubled by planting in rows rather than by broadcast and by weeding twice rather than not weeding, which is the usual practice. Soils in the Buberuka highlands (Yamoah et al., 1990) are characterized by low fertility and acidity (pH 3.5-6.5). This likely contributes to low yields, but these soil characteristics are too vague to be used as selection criteria in the wheat improvement program. Wheat also is grown on slopes of 4 to 76% with different azimuths. These factors, too, are possible yield constraints.

Objectives of this study were to: (i) identify factors related to wheat yield on farm fields in the Buberuka highlands of Rwanda so that the wheat improvement program might address important yield constraints in the selection process and (ii) develop an understanding of the yield-site characteristics relationship to enhance cultivar selection techniques.

MATERIALS AND METHODS

Twenty-five farm fields were selected in 1988 and 30 fields in 1988-1989. Each field was about 300 m^2. In 1988 wheat was planted in March and harvested in August. For the 1989 season, wheat was planted in Sept. 1988 and

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harvested in Feb. 1989. In Rwanda, two crops of wheat are grown during a 12-mo. period. All fields were characterized for plant disease development, exchangeable acidity, exchangeable cation concentration, pH, percent slope, field azimuth (in degrees where north = 360 and south = 180) and irradiance (MJ/m²/day) incident on each field during the growing seasons. Wheat foliar diseases were monitored by making visual estimates (James, 1975) of severity (expressed as the fraction of diseased foliar surface [0-1] where 0 refers to no symptoms and 1 to the entire foliar surface being diseased) on all laminar tissue at booting (GS 45), anthesis (GS 65) and dough (GS 83) stages. Area under the disease progress curve (AUDPC)[2] was calculated for each disease as $(X_i + [X_{i+1}]/2) \times (T_{i+1} - T_i)$ where X_i is the proportion of tissue showing symptoms at time T_i and X_{i+1} is the proportion at time T_{i+1} (Shaner and Finney, 1977). Time was expressed in days from the first observation.

Ten soil samples were taken from each field to a depth of 15 cm, bulked and analyzed for pH (Peech, 1965), exchangeable acidity as Al and H (Barnhisel and Bertsch, 1982), exchangeable cations as Ca, Mg, Na and K (Thomas, 1982), available P (Bray and Kurtz, 1945), percent total N (Bremner and Mulvaney, 1982) and percent organic C (Walkley and Black, 1934). Effective cation exchange capacity (ECEC) was calculated as Ca + Mg + K + Na + Al + H, and the C/N ratio as percent organic C/percent total N.

Solar radiant flux, S_{tl}, was calculated on each field by methods of Kondratyev (1969).

$$S_{tl} = S_m \cos i$$

where i is the angle of incidence of the solar ray and S_m is the solar radiation flux perpendicular to the incoming beam at the earth's surface corresponding to the atmospheric mass m. For tilted fields with slope α and an azimuth of ψ_n, i is given by

$$\cos i = \cos \alpha \sin h_o + \sin \alpha \cos h_o \cos \psi$$

where h_o is the altitude of the sun and ψ is the difference in azimuth between the field and the azimuth of the sun, ψ_o, with $\psi = \psi_o - \psi_n$. The ψ_n is defined by the projection of a normal to the field onto a horizontal surface.

The solar azimuth and latitude were calculated using

$$\sin h_o = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \Omega$$

$$\cos \psi_o = \frac{\sin h_o \sin \phi - \sin \delta}{\cos h_o \cos \phi}$$

$$\sin \psi_o = \frac{\cos \delta \sin \Omega}{\cos h_o}$$

where ϕ is the latitude of Rwanda, -2°, δ is the declination of the sun and Ω is the solar hour angle. Solar declination was calculated using

$$\sin (\delta) = \sin \varepsilon \sin \lambda$$

where ε is the obliquity of the sun, 23° 25' 39.21" and λ is the heliocentric longitude (Astronomical Almanac, 1989).

We did not calculate the contribution of diffuse solar radiation to S_m because the diffuse radiation field is isotropic, and thus, the contribution of diffuse radiation is independent of field slope and azimuth.

We calculated S_m using the American Society of Heating, Refrigerating, and Air-Conditioning Engineers algorithm (Iqbal, 1983), $S_m = S_r e^{-B(\sec z)}$, where S_r is the solar constant at a distance r from the sun, z is the zenith distance, and B is the overall broadband value of the atmospheric transmission coefficient, a value of 0.164 for B from Iqbal (1983).

$$S_r = S(1 + .033 \cos (2\pi d_n/365)).$$

The solar constant S, 1360 J/m²/sec, was corrected as outlined in Iqbal (1983) and applied to the changing earth-sun distance, and d_n is the day number of the year, ranging from 1 on 1 January to 365 on 31 December. Since our fields were at different elevations, we multiplied B by P_t/P_o), where P_t is the atmospheric pressure of our field and P_o is the standard atmospheric pressure (Iqbal, 1983)

We calculated the total integrated flux falling on each field during each day by integrating S_{tl} over the time period of solar illumination. We calculated the total flux, which fell on each field during the entire growing season, by summing the contribution of each day.

Tillers and spikes were counted in four 0.25-m² areas in each field; grains were counted in 5 spikes/area and grain weights taken from each area at crop maturity. Kernel weight was calculated as grain weight (grams/m²)/number of spikes/m² times the number of grains/spike. Yield was expressed as (i) number of tillers/m², (ii) number of spikes/m², (iii) number of grains/spike, (iv) kernel weight in grams/kernel, and (v) grain weight in kg/ha.

[1]Abbreviations: AUDPC, area under the disease progress curve; ECEC, effective cation exchange capactiy; OLS, ordinary least squares; and SPR, standard partial regression.

Yield data were regressed (ordinary least squares methods-OLS) on all soil, site and disease factors (independent variables) singly and in combination for 1988, 1989 and for combined seasons by using the Multivariate General Linear Hypothesis program in SYSTAT - System for Statistics (Wilkinson, 1987). The independent variable or set of variables that best explained variation in yield and yield components was determined from coefficients of determination (R^2) and standard errors of the estimate (Sy.x) for the model tested. The relative importance of independent variables in regression equations was reflected by the OLS standard partial regression (SPR) coefficients whereas Student's *t* test ($P = 0.05$) was used to test the homogeneity of regression coefficients for the same variable among seasons and among yield components (Steel and Torrie, 1960). Variables with similar coefficients among seasons and among yield components were considered the most stable and, therefore, the most reliable as selection criteria for the wheat improvement program. Principal components regression was used to test for collinearity among variables and to eliminate from the models variables that were not independent (Williams et al., 1979). Homogeneity of variance was tested from residuals associated with each model. Therefore, the variable or variable set selected to model yield and yield components exhibited minimum collinearity and had the most stable regression coefficients among seasons and among yield components.

RESULTS

Mean wheat yield was 1400 kg/ha for 1988 and 840 kg/ha for 1989 (Tables 1 and 2). Soils were acid and high in exchangeable Al. Total N, P, K, Ca, Mg and Na were within the concentration ranges expected for oxisols in the region (Yamoah et al., 1990) but inadequate for normal crop production (Singh, 1979). Foliar diseases (stripe rust, caused by *P. striiformis*; powdery mildew, caused by *E. graminis* f. sp. *tritici*; and leaf rust, caused by *P. recondita* f. sp. *tritici*) were present. Maximum severity at soft dough stage was <0.30 in 1988 and 0.62 in 1989. Powdery mildew, dominant in 1989, shared dominance with leaf rust and stripe rust in 1988. Severities of tan spot (caused by *Pyrenophora tritici-repentis* (Died.) Drechs.) and Septoria leaf blotch (caused by *Mycosphaerella graminicola* (Funkel) Schroeter) did not exceed a trace (data not shown).

Aluminum and N explained a significant amount of variation in number of tillers/m^2 and spikes/m^2 for 1988 (Tables 3 and 4) whereas percent slope and stripe rust explained the most in 1989. When data were combined, the significant variable set was a combination of the two seasons with the exception that powdery mildew also emerged as a significant factor. The magnitude of R^2 (0.35) indicated that most of the variation in tiller and spike numbers in 1988 was not explained by Al and N. Total N was particularly stable, as shown by regression coefficients. Coefficients were 350 and 432 for tiller numbers and 299 and 377 for spike numbers in 1988 and combined seasons, respectively. Aluminum also was stable, and coefficients were -18 and -11 for tiller numbers and -18 and -10 for spike numbers in 1988 and combined seasons, respectively. Tillers and spikes/m^2 also were correlated ($r = 0.35$) with irradiance as a second degree polynomial, and maximum numbers occurred at about 28 MJ/m^2/day (Figs. 1 and 2).

Grain number/spike was associated with field azimuth in 1989 and for combined seasons (Table 5). In 1988, leaf rust severity and pH were significant variables, but they were not represented in 1989 or for combined seasons. Regression coefficients for field azimuth were 0.03 and 0.03 in 1989 and combined seasons, respectively (Table 8), indicating the stability and, therefore, reliability of azimuth as a candidate factor for prediction of grain number/spike. The sign of the regression coefficient for azimuth was positive, indicating that grains/spike increased as field azimuth changed from 30 to 330 degrees (range of field azimuth encountered). The SPR coefficient for azimuth in 1989 was larger than for Al and N (Table 5), indicating the relative importance of azimuth for that season. Aluminum and N emerged as significant variables for grains/spike in 1989, and the SPR coefficient for N (0.39) was similar to coefficients for tiller and spike numbers. This supports the reliability of N (responsiveness) as a selection criterion for wheat improvement in the Buberuka.

Kernel weight in 1988 was correlated with total AUDPC for all diseases and with N, but in 1989 and for combined seasons, azimuth and slope were significant factors (Table 6). Regression coefficients for AUDPC, slope and N were negative whereas the coefficient for azimuth was positive. Area under the disease progress curve and N explained 64% of the variability in kernel weight in 1988, but azimuth and slope explained only 25 and 21% in 1989 and for combined seasons, respectively.

Irradiance was correlated with grain yield in 1988 whereas azimuth and slope explained 41% of the variability in yield for 1989 (Table 7). Regression coefficients for azimuth associated with yield, grains/spike and kernel weight were different (Table 8) although SPR coefficients were similar, suggesting that the importance of azimuth relative to other variables in the model is similar for grains/spike, kernel weight and yield. When data from the two seasons were combined, slope, azimuth and pH emerged as the best variable set to explain variability in yield ($R^2 = 0.31$), although most of the variability remained unexplained.

Generally, standard errors of the estimate (Sy.x) for yield components were smaller in 1989 than in 1988, indicating that season 1989 was less variable than season 1988.

There was no predictive advantage to expressing disease as AUDPC rather than as severity except for kernel weight in 1988. Generally, when disease severity was significant (for tillers, spikes and grains/spike), AUDPC could have been substituted for severity with no loss or gain in model precision. Severity was retained in most models, therefore, because only one observation is required (at dough stage) rather than several for the calculation of AUDPC.

DISCUSSION

Stripe rust commonly is severe at the principal research station where selection for wheat improvement is done, and promising lines emerging from the program show good resistance. Disease severity on farm fields seldom exceeded 30% during our study; nevertheless, stripe rust and powdery mildew emerged as significant variables for tiller and spike numbers in 1989 when maximum severities were 0.57 and 0.62 for stripe rust and powdery mildew, respectively. Leaf rust severity was correlated with grain number/spike and AUDPC for stripe rust, leaf rust and powdery mildew combined was a significant factor associated with kernel weight in 1988. Wheat leaf rust is known to reduce kernel number per spike and kernel weight (Subba Rao et al., 1989), and stripe rust reportedly reduces kernel weight (King, 1976). Powdery mildew on barley reduces spikes/m^2 and kernel weight but not grains/spike (Jenkyn, 1974). Our results, therefore, are similar to those from other studies and confirm the importance of selection for disease resistance. However, N and Al also were significantly correlated with most yield components in at least one season, suggesting that tolerance to Al toxicity and responsiveness to N also would have a measurable impact on cultivar performance and should be used as selection criteria as well.

It is spurious to conclude that model components were causative in nature because they explained a significant portion of the variability in tiller and spike numbers. Nevertheless, the model components confirmed by principal components regression as being the smallest, most reliable set of variables also explained a significant amount of the variability in the dependent variables, even though model components did not always constitute the best predictive model.

The smallest, most reliable variable set for grains/spike explained 53 and 59% of the variation for 1988 and 1989, respectively. When data were combined, only azimuth emerged as a significant variable. The model predicts more grains/spike as field azimuth increases. Azimuth also was positively correlated with kernel weight and grain yield for at least one season. The relationship of azimuth to grain yield and yield components is complex and appears to be mediated primarily by irradiance (MJ/m^2/day). On the steep slopes of Rwanda, azimuth and irradiance are related as a second-degree polynomial with peak irradiance occurring on the south-facing fields during the growing season September to February (1989) and on north-facing fields during the season March to July (1988) (Fig. 3A and B). Optimal irradiance for spike information (28 MJ/m^2/day) occurred on fields with azimuths of about 68 and 290°, so the theoretical relationship between the spike numbers and azimuth should best be expressed by a second-degree polynomial model. However, spike numbers and azimuth best fit a linear model (r = -0.36; P =0.008) with a negative regression coefficient. That relationship is best understood as being influenced by field slope, which is negatively correlated with irradiance. In this study, however, slope was positively correlated with azimuth. Based on irradiance, therefore, spikes/m^2 in west-facing and in east-facing fields should be similar, but because west-facing fields generally were steeper than east-facing fields, spike numbers were lower than expected. The increases in grains/spike and kernel weight with azimuth are perhaps then forms of compensation, with plants being sink limited (fewer spikelets) in fields with more spikes/m^2 (low azimuth values) but source limited in fields with fewer spikes/m^2 but more spikelets/spike (high azimuth values). The simultaneous control of grain yield by sink and source phenomena has been reported (Thorne, 1974; Brocklehurst, 1977; Gaunt, 1980), and although controversy still exists regarding the relative importance of sink vs. source hypotheses, they are not exclusive and may in fact work in unison. The negative correlation of soil N with kernel weight also might be explained by compensation as soil N was positively correlated with tillers and spikes/m^2.

Field slope was negatively correlated with tillers/m^2, spikes/m^2, kernel weight and grain yields; as slope increased, yield and yield components decreased. Because the Buberuka highlands of Rwanda are characterized by steep slopes and high rainfall (1200 mm/yr), soil erosion is severe and soil productivity is declining (Franzel et al., 1985; Yamoah et al., 1990).

SUMMARY

Responsiveness to soil N and tolerance to Al toxicity are important selection criteria for wheat in the Buberuka highlands. But the continued search for resistance to *P. striiformis* and to *E. graminis* f. sp. *tritici*, particularly juvenile plant resistance, is needed since disease effects were most closely associated with yield components completed prior to anthesis. Improved yield also could be obtained from lines that tillered well under high irradiance, particularly on fields

with north and south azimuths. Finally, the wheat improvement program should use early generation testing sites representative of the region rather than rely on performance data from the main experiment station as criteria for cultivar release and dissemination.

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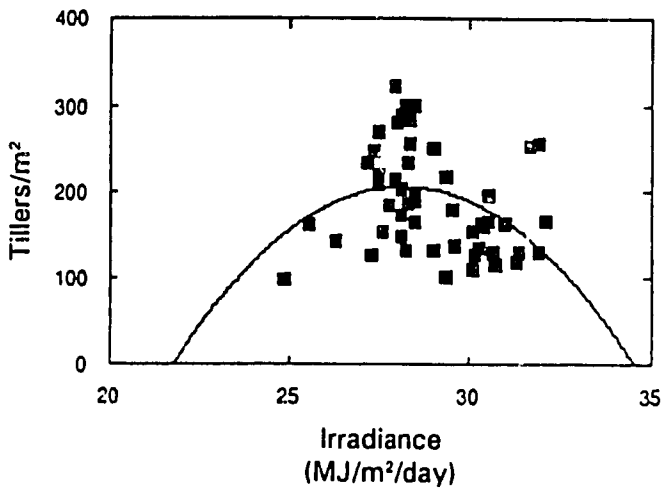

Fig. 1. Relationship of till/m² to irradiance as MJ/m²/day for seasons 1988 and 1989 in the Buberuka Highlands of Rwanda.

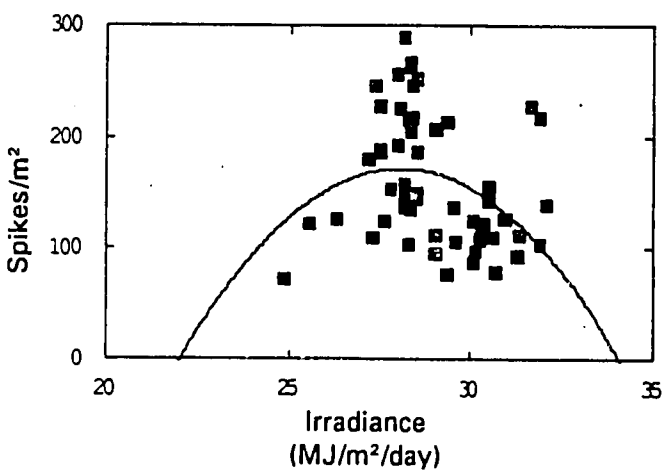

Fig. 2. Relationship of spikes/m² to irradiance as MJ/m²/day for seasons 1988 and 1989 in the Buberuka Highlands of Rwanda.

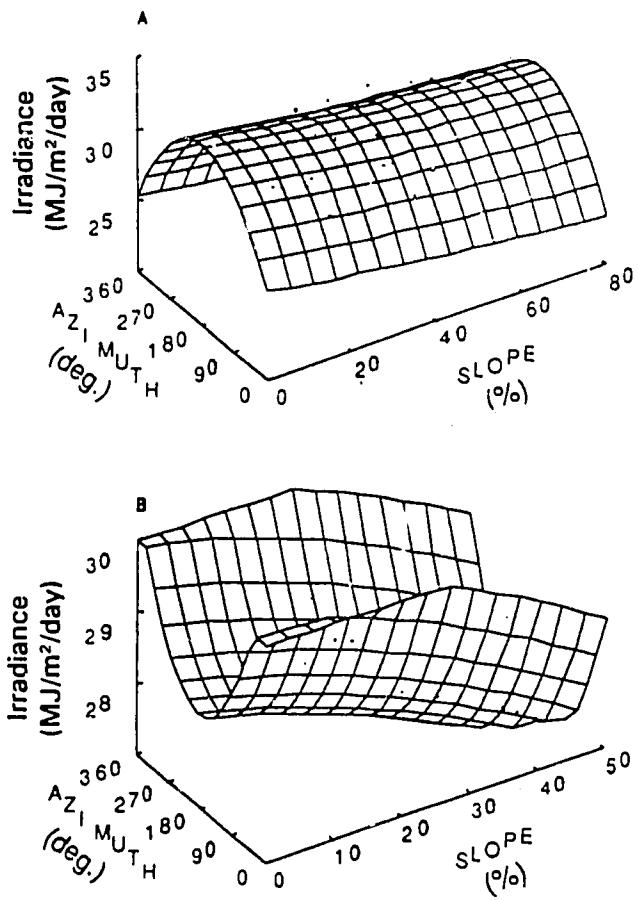

Fig. 3. Relationship of irradiance, field azimuth and field slope in the Buberuka Highlands of Rwanda. A) For season 1989 - September to February and B) For season 1988 - March to July.

Table 1. Minimum, maximum and mean values and standard deviations for wheat yield components (dependent variables) and for soil, site and disease factors (independent variables) from the 1988 season in the Buberuka Highlands of Rwanda.

Variable	n[1]	Min.	Max.	Mean	Std. dev.
Tillers/m^2	25	99	320	231	57
Spikes/m^2	25	81	289	199	51
Grains/spike	11	13	30	20	5
Grain wt (kg/ha)	11	720	2240	1400	560
Kernel wt (g/kernel)	11	0.02	0.04	0.03	0.01
Field slope (%)	24	4	45	23	11
Field azimuth (deg)	24	45	270	128	75
Irradiance (MJ/m^2/d)	24	27	29	28	5
pH	25	3.5	6.5	4.2	0.8
Al (cmol/kg)	25	0.00	5.55	1.96	1.62
H (cmol/kg)	25	0.08	0.98	0.46	0.28
Ca (cmol/kg)	25	1.10	19.36	4.17	3.62
Mg (cmol/kg)	25	0.29	2.47	1.21	0.62
K (cmol/kg)	25	0.05	1.69	0.23	0.35
NA (cmol/kg)	25	0.01	0.11	0.04	0.02
ECEC[2]	25	3.20	23.60	7.59	3.66
Organic C (%)	25	0.50	4.79	2.41	0.82
Total N (%)	25	0.14	0.36	0.26	0.06
C/N	25	3.0	13.0	9.0	2.1
P (mg/kg)	25	0.35	135.00	11.12	24.77
Stripe rust[3]	25	0.00	0.20	0.01	0.04
Leaf rust[3]	25	0.00	0.22	0.03	0.06
Powdery mildew[3]	25	0.00	0.27	0.02	0.06
AUDPC[4]-stripe rust	25	0.0	1.8	0.1	0.4
AUDPC-leaf rust	25	0.0	2.6	0.3	0.7
AUDPC-powdery mildew	25	0.0	4.6	0.3	0.9

[1]n = number of fields

[2]Effective cation exchange capacity

[3]Disease values given as the fraction (0-1) of foliar tissue showing symptoms at soft dough stage (GS 83)

[4]AUDPC = area under the disease progress curve

Table 2. Minimum, maximum and mean values and standard deviations for wheat yield components (dependent variables) and for soil, site and disease factors (independent variables) from the 1989 season in the Buberuka Highlands of Rwanda.

Variable	n[1]	Min.	Max.	Mean	Std. dev.
Tillers/m²	30	99	254	152	41
Spikes/m²	30	71	227	122	38
Grains/spike	26	13	29	22	4
Grain wt (kg/ha)	26	280	1440	840	310
Kernel wt (g/kernel)	26	0.02	0.06	0.03	0.01
Field slope (%)	29	9	76	34	18
Field azimuth (deg)	30	30	330	194	94
Irradiance (MJ/m²/d)	30	25	32	29	2
pH	30	3.6	4.7	4.0	0.3
Al (cmol/kg)	30	0.03	4.23	2.05	1.40
H (cmol/kg)	30	0.05	0.90	0.35	0.24
Ca (cmol/kg)	30	0.09	4.60	1.76	1.09
Mg (cmol/kg)	30	0.10	1.79	0.79	0.42
K (cmol/kg)	30	0.01	0.32	0.10	0.06
NA (cmol/kg)	30	0.00	0.09	0.04	0.02
ECEC[2]	30	3.16	6.81	5.08	0.92
Organic C (%)	30	1.40	3.63	2.19	0.45
Total N (%)	30	0.14	0.30	0.21	0.04
C/N	30	8.0	12.0	10.1	2.2
P (mg/kg)	30	0.35	11.55	3.39	2.45
Stripe rust[3]	30	0.00	0.57	0.05	0.13
Leaf rust[3]	30	0.00	0.23	0.05	0.06
Powdery mildew[3]	30	0.01	0.62	0.27	0.16
AUDPC[4]-stripe rust	30	0.0	13.7	1.0	3.0
AUDPC-leaf rust	30	0.0	8.9	0.9	1.8
AUDPC-powdery mildew[4]	30	0.1	11.5	5.9	3.7

[1]n = number of fields
[2]Effective cation exchange capacity
[3]Disease values given as the fraction (0-1) of foliar tissue showing symptoms at soft dough stage (GS 83)
[4]AUDPC = area under the disease progress curve

Table 3. Independent variables associated with number of tillers/m² in 1988, 1989 and combined seasons, number of fields (*n*), standard partial regression coefficients (B_1), coefficients of determination (R^2), standard errors of the estimate (Sy.x) and alpha level (*P*) from the regression analysis of soil, site and disease factors on wheat yield components.

Season	Variable	*n*	B_1	R_2	Sy.x	*P*
1988	Al	25	-0.53	0.35	47.86	0.009
	N		0.37			
1989	Field slope	29	-0.48	0.30	36.15	0.010
	Stripe rust		-0.33			
Combined	N	53	0.38	0.55	44.31	<0.001
	Powdery mildew		-0.33			
	Al		-0.25			
	Stripe rust		-0.24			
	Field slope		-0.23			

Table 4. Independent variables associated with number of spikes/m² in 1988, 1989 and combined seasons, number of fields (*n*), standard partial regression coefficients (B_1), coefficients of determination (R^2), standard errors of the estimate (Sy.x) and alpha level (*P*) from the regression analysis of soil, site and disease factors on wheat yield components.

Season	Variable	*n*	B_1	R_2	Sy.x	*P*
1988	Al	25	-0.56	0.36	42.94	0.007
	N		0.35			
1989	Field slope	29	-0.48	0.30	33.50	0.010
	Stripe rust		-0.33			
Combined	Powdery mildew	53	-0.37	0.56	41.24	<0.001
	N		0.35			
	Al		-0.25			
	Stripe rust		-0.23			
	Field slope		-0.23			

Table 5. Independent variables associated with number of grains/spikes in 1988, 1989 and combined seasons, number of fields (*n*), standard partial regression coefficients (B_1), coefficients of determination (R^2), standard errors of the estimate (Sy.x) and alpha level (*P*) from the regression analysis of soil, site and disease factors on wheat yield components.

Season	Variable	*n*	B_1	R_2	Sy.x	*P*
1988	Leaf rust	11	-0.65	0.53	3.68	0.049
	pH		-0.45			
1989	Field azimuth	26	0.67	0.59	2.78	<0.001
	Al		-0.52			
	N		0.39			
Combined	Field azimuth	36	0.64	0.43	3.17	<0.001

Table 6. Independent variables associated with kernel weight (g/kernel) in 1988, 1989 and combined seasons, number of fields (*n*), standard partial regression coefficients (B_1), coefficients of determination (R^2), standard errors of the estimate (Sy.x) and alpha level (*P*) from the regression analysis of soil, site and disease factors on wheat yield components.

Season	Variable	*n*	B_1	R_2	Sy.x	*P*
1988	AUDPC[1]-all diseases	11	-0.93	0.64	0.004	0.016
	N		-0.53			
1989	Field azimuth	25	0.53	0.25	0.01	0.044
	Field slope		-0.48			
Combined	Field azimuth	36	0.49	0.21	0.009	0.022
	Field slope		-0.39			

[1]AUDPC = area under the disease progress curve.

Table 7. Independent variables associated with yield (kg/ha) in 1988, 1989 and combined seasons, number of fields (*n*), standard partial regression coefficients (B_1), coefficients of determination (R^2), standard errors of the estimate (Sy.x) and alpha level (*P*) from the regression analysis of soil, site and disease factors on wheat yield components.

Season	Variable	*n*	B_1	R_2	Sy.x	*P*
1988	Irradiance	11	-0.65	0.42	45.38	0.032
1989	Field azimuth	25	0.67	0.41	23.57	0.003
	Field slope		-0.63			
Combined	Field slope	36	-0.51	0.31	41.10	0.007
	Field azimuth		0.37			
	pH		0.32			

Table 8. Homogeneity of regression for independent variables appearing most frequently in models from the analysis of soil, site and disease factors on wheat yield components.

Yield component	Total nitrogen (%) Season			Aluminum (cmol/kg) Season		
	1988	1989	Combined	1988	1989	Combined
Tillers/m²	350 ab[1]	--[2]	431 a	-18 a	--	-10 a
Spikes/m²	299 ab	--	376 a	-17 a	--	-9 a
Grains/spike	--	42 b	--	--	-2 b	--
Kernel wt	-0.04 c	--	--	--	--	--
Grain wt (kg/ha)	--	--	--	--	--	--

Yield component	Slope (%) Season			Azimuth (degrees) Season		
	1988	1989	Combined	1988	1989	Combined
Tillers/m²	--	-1.11 a	-0.92 a	--	--	-0.25 a
Spikes/m²	--	-1.04 a	-0.84 a	--	--	-0.23 a
Grains/spike	--	--	--	--	0.03 b	0.03 b
Kernel wt	--	>-0.01 b	>-0.01 b		>0.01 c	>0.01 c
Grain wt (kg/ha)	--	-0.99 a	-1.32 a	--	0.22 a	0.20 a

Yield component	Stripe rust severity Season			Powdery mildew severity Season		
	1988	1989	Combined	1988	1989	Combined
Tillers/m²	--	-99 a	-140 a	--	--	-115 a
Spikes/m²	--	-91 a	-128 a	--	--	-123 a
Grains/spike	--	--	--	--	--	--
Kernel wt	--	--	--	--	--	--
Grain wt (kg/ha)	--	--	--	--	--	--

[1]Values followed by the same letter for an independent variable are not significantly different according to Student's *t* test at $P = 0.005$.

[2]Variable nonsignificant at $P = 0.005$.