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Effect of Soil and Climatic Conditions on Brown Spot Occurrence in Rice Lowland across Four Agro-climatic Zones of Côte d'Ivoire

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To evaluate interaction of soil pH and acidity with weather on Rice Brown spot (BS) occurrence in rice lowlands.

Study Design: Cross sectional study.

Place and Duration of Study: Four distinct rice lowlands belonging to different climatic zones (forest, transitional and savanna) of Côte d'Ivoire during cropping seasons of 2021.

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Methodology: BS characterization were done in different farmer fields where soil samples were also collected during dry and rainy seasons. Soil silicon and acidity were determined in those samples and rice grain yield at harvest time were recorded in different sites. Weather data related to sites and seasons were used to find out correlations.

Results: Occurrence of BS was found in forest zones with scores of 4 and 3 compared to 1 and 2 in savanna and transitional zones, respectively, with seasonal variation. Both rice production and the occurrence of BS were explained by soil parameters in conjunction with climatic parameters. Rainfall (R=0.38) and relative humidity (R=0.64) leaded BS occurrence and decrease of yield. Wind speed (R=0.62) and air maximum temperature (R= 0.63) were the determinant factors affecting rice yields. Si was found to be a component of sustainable soil management that interferes with soil pH in all climatic zones. Combined with Temperature, both soil parameters predicted BS occurrence over 50%.

Conclusion: Temperature decrease BS pathogens occurrence whereas high humidity increases its spread. Those parameters combined with silicon which interferes with pH could leads sustainable solutions in BS control. Furthermore, having a deep understanding with rice varietal considerations can significantly improve strategies related to rice cultivation and protection.

Keywords: Precision agriculture; disease forecasting; rice; brown spot; silicon.

1. INTRODUCTION

Rice production is crucial for ensuring food security and providing essential nutrients to millions of people in Africa [1]. However, the expansion of rice production has been accompanied by the emergence of various biotic factors, including fungal diseases such as brown rice spot (BS), which significantly reduce crop yields. Rice brown spot is a major disease affecting rice production in several African countries, including Côte d'Ivoire, where it occurs in different agro-climatic zones with varying severity [2–6]. The disease causes necrotic lesions on leaves, panicles and grains, resulting in reduced photosynthesis and subsequent yield reduction up to 30% [5,7–9].

Factors such as temperature, humidity, rainfall, wind and soil status all play a crucial role in the occurrence and severity of brown spot in rice fields [10]. Temperature and high humidity significantly affect the development of brown spot from seed storage to the various vegetative stages, and wind can easily move spores from diseased to healthy plants in farms [11,12]. The survival of the pathogen in rice canopy bays when lesions are present is associated with rainfall patterns and leaf wetness [13]. The frequency of disease occurrence is greatest in dry soil, lowest in wet soil, and moderate in moist soil [11]. Soils that are also deficient in silica, potassium, manganese, or magnesium, as well as the presence of hydrogen sulfide, make plants more susceptible to infection [14]. When these conditions are met, excessive amounts or lack of nitrogen with an increase in phosphorus present in the soils favor the appearance of BS, especially during the end of tillering [15,16]. The presence of silicon in a rice soil promotes growth, yield and disease resistance, especially against rice diseases, highlighting its importance in the regulation of brown spot disease with different responses under climate variability [7,17,18]. Soil acidity (pH) indirectly affects disease spread by influencing nutrient availability and uptake, with effects that can also vary from beneficial to detrimental [19].

However, the interactions between these different factors and their spatio-temporal variations remain poorly understood in the different agro-climatic zones of Côte d'Ivoire despite the long history of the disease in this region. This lack of understanding poses a major threat to rice production, as the disease outbreak can lead to severe losses, especially in weather favorable conditions. In addition, the increasing frequency of global warming and erratic rainfall may lead to a more severe manifestation of brown spot, ultimately could result higher yield reductions [20]. There is therefore an urgent need to study the interactions between climate and soil variability and their impact on the occurrence of BS in different agro-climatic zones of Côte d'Ivoire. Such a study will allow a better understanding of the mechanisms of BS development and the development of effective management strategies to control the disease. This study aims then to explore the impact of soil acidity and silicon concentration on BS occurrence in rice fields across various climatic zones in Cote d’Ivoire. The objectives are to (i) characterize BS occurrence in different climatic zones, and (ii) establish the relationship between BS severity and soil conditions, independent of rice genetic diversity, while considering weather factors.

2. MATERIALS AND METHODS

2.1 Study Areas

Field surveys were conducted in major rice cropping lowlands in Gagnoa, Bouaké, Agboville, and Korhogo, localized respectively in South-West, Center, South-East and North parts of Côte d'Ivoire. Located in forest zone, Gagnoa and Agboville share a bimodal rainfall regime with an average temperature of 23.5±13.4°C, while Bouaké in transitional zone has a tropical climate with a bimodal rainfall regime of around 1200 mm per year. Korhogo, in sudanian area has a unimodal rainfall regime of less than 1200 mm per year with high temperatures up to 33°C. Rice was cultivated in dry and rainy seasons following different cultural calendars as explained in Table 1. Soil properties of different areas are summarized in Table 2.

2.2 BS Disease on Rice Leaves on Field

93 rice farms were surveyed during rice cropping seasons of 2021, with 22 in Gagnoa, 25 in Bouaké, 19 in Agboville, and 27 in Korhogo. These farms cultivating moderate to susceptible rice cultivars to BS were selected on basis of cultivated area size (at least 1.24 acres) and were chosen based on the normal approximation of the binomial distribution [21].

BS characterization was evaluated on rice leaves at the onset of the reproductive stage in 2-4 randomly chosen stands of rice from different farmers' fields. Based on surface covered by brown spots on rice leaves, severity scores were recorded using the IRRI (2014) scale on 10 plants per 1 m² plot, designed twice per stand as mentioned in Table 3. The average score of each surveyed field was retained.

Table 1. Climatic characteristics and rice cultivation periods of different localities in 2021

Locality	Agro climatic zone	Dry Season	Rainy Season	Rainfall pattern
Agboville	Forest Zone (Eastern)	December-March	August –November	Bimodal
Bouaké	Sudano-Giuinean	February- May	September-December	Bimodal
Gagnoa	Forest zone (Western)	March-June	September-December	Bimodal
Korhogo	Sudanian	February-May	August –November	Unimodal

Table 2. Soil Chemical properties for different areas

Soil nutrients	Agboville	Gagnoa	Bouaké	Korhogo
C-org ($g.kg^{-1}$)	11.27	9.25	11.94	12.26
K (cmol/kg)	0.02	0.008	0.016	0.01
Total-P (ppm)	4165	5297	4004	7056
Ca (cmol/kg)	0.80	1.14	1.59	0.46
Mn (ppm) Mn 36.38 %	64.08	--	112.28	100.01
Fe_2O_3 (ppm) 70% Fe	38511.43	29102.86	21060	59650

-- Not significant values.

C-org,; K, Total-P, Ca, Mn and Fe_2O_3 represent organic carbon, potassium, total phosphorus, calcium, maganese and iron rates in different areas.

Table 3. Scale for brown spot disease of rice (IRRI, 2014)

Disease scale	Infection
0	No incidence
01	1–5%
02	6–15%
03	16–25%
04	26–50%
05	> 50%

2.3 Soil Analysis and Rice Yield

Ninety-three (93) composite soil samples were collected per season from a depth of 0-20 cm per plot by mixing samples from different plots. After air drying, the soil samples were ground, sieved with a 2 mm sieve, and analyzed in the laboratory. The actual soil pH (pH_{H2O}) and potential soil pH (pH_{KCl}) were determined using a glass pH meter (HANNA) for a 1:2.5 soil-solution ratio. The total concentration of Si (SiO_2) was determined by portable X-ray fluorescence spectrometry analysis using dry soil samples with less than 20% moisture. This method is accurate in determining the total elemental concentration in dry soil samples [22].

Values of SiO_2 (MV) were converted to Silicon (Si) concentration (cmol/kg) according to following equations as bellow:

(1) Determination of molar number of SiO_2 according to molar weight (60.08g):

$$\frac{\mathrm{MV}}{60.08.\mathrm{E}{-3}} \tag{1}$$

(2) Determination of Si concentration (46.7%) in the molar number of SiO_2 as calculated above:

$$\frac{\mathrm{MV}\times 46.7}{60.08.\mathrm{E}{-5}} \tag{2}$$

During the harvest period, fresh weight of rice grains was measured and air-dried for a few days to determine the dry weight (DW). Moisture content (H) was measured by oven drying the rice grains for 24 hours at 70°C. Yield (Y) was estimated in tons per hectare using the following formula:

$$\mathrm{Y} = \mathrm{DW} * \left(\frac{10000}{1000}\right) * \left(\frac{100-\mathrm{H}}{86}\right) \tag{3}$$

Y= Yield in tons/ha; *DW*= Dry weight in Kg; *H*=Humidity rate in %

2.4 Climate Data

Daily data for Maximum (Tmax), Mean (Tmean), and Minimum temperature (Tmin), Relative humidity (RH), Rainfall (Precip), and Wind speed (WS) were download from POWER | Data Access Viewer (nasa.gov) for different locations with a spatial coverage of $1/2^{o}$ $*1/2^{o}$. Monthly averages were generated and adjusted for each cropping season.

2.5 Statistical Analyses

Data analysis was implemented using R software (Version 4.1.0). Non parametric Kruskal-Wallis and Dunn tests determined differences and homogenous groups between BS, rice yield, soil and weather. ANOVA analyzed effects across site-seasons on BS severities and paddy yield [23]. Spearman correlation analyses explained relationships between BS severity/rice yield and climate/soil parameters [24]. Regression analyses were established with significant explanatory variables for dependent variables [25]. Confusion matrix evaluated model accuracy.

3. RESULTS

3.1 Environmental Conditions during Rice Cropping Seasons

Daily fluctuations of environmental factors throughout seasons illustrated by Fig. 1, showed noticeable distinctions between the dry and rainy seasons in Korhogo followed by Bouaké, compared to Agboville and Gagnoa. Rainfall was high in the first semester in Gagnoa while Bouaké and Agboville had more dispersed peaks. RH was more stable in the wet season than the dry season, with the lowest average recorded in Korhogo during the dry season.

In the dry season, temperature and wind speed were high. Table 4 shows weather parameter means for wet and dry seasons across localities. Korhogo and Bouaké had the highest average temperatures, reaching 28.8 and 28.1°C, respectively, while Agboville and Gagnoa had the highest rainfall amounts of 736 mm to 980 mm and RH above 80% during the rainy season.

3.2 Soils Acidity and Silicon Content in Areas

Soil across the studied areas had almost neutral active acidity (pH 6.6-6.7), with the lowest value at Korhogo (pH 6.3). Exchangeable acidity was stable (6.3) except for Korhogo (6.0). Similar ΔpH values were observed between Agboville and Korhogo (0.3) and Bouaké and Gagnoa (0.4), respectively. Soil silicon concentration (2.13-2.28 cmol/kg) was higher in the forest zone (Agboville and Gagnoa) compared to transitional and savanna zones (Bouaké and Korhogo).

Table 4. Weather during rice cropping seasons in year 2021

	Mean Temp (°C)		**Max Temp (°C)**		**Min Temp (°C)**		**Rainfall (mm)**		**Relative Humidity (%)**		**Wind speed (m/s)**	
	Dry	**Rainy**	**Dry**	**Rainy**	**Dry**	**Rainy**	**Dry**	**Rainy**	**Dry**	**Rainy**	**Dry**	**Rainy**
Agboville	26.75 ±0.77	25.61 ± 0.54	31.59 ± .56	29.41 ± 0.94	23.1 ± .76	22.66 ±0.77	346.32 ± 4.21	980.76 ± 22.3	82,08 ± 4.35	88.66 ± 2.91	1,50 ±0.35	1.57 ±0.48
Bouaké	28.1 ±1.31	25.61 ±0.77	33.5 ±2.45	29.90 ± 1.13	23.5 ±1.12	21.85 ±1.30	394.2 ± 4.70	435.60 ±8.79	70,27 ± 10.5	82.93 ±7.05	1,73 ±0.38	1.28 ±0.33
Gagnoa	25.9 ±0.79	25.48 ±0.64	29.9 ±1.49	29.50 ±1.36	22.9 ±0.65	22.31 ±0.63	557.1 ± 5.5	736.65 ±14.19	86,38 ± 3.77	87.40 ±5.12	1,01 ±0.16	0.88 ±0.21
Korhogo	28.8 ±1.35	26.25 ±1.19	35.7 ±2.33	31.69 ±2.83	22.8 ± 4.9	21.82 ±0.71	257.6 ± 4.9	488.21 ±8.40	54,68 ± 15.8	76.50 ±9.03	2,02 ±0.43	1.68 ±0.41

**Mean Temp= Mean temperature; Max Temp= Maximum temperature; Min Temp= Minimum temperature. Data presented are the means ± standard deviations (Sds) for different regions*

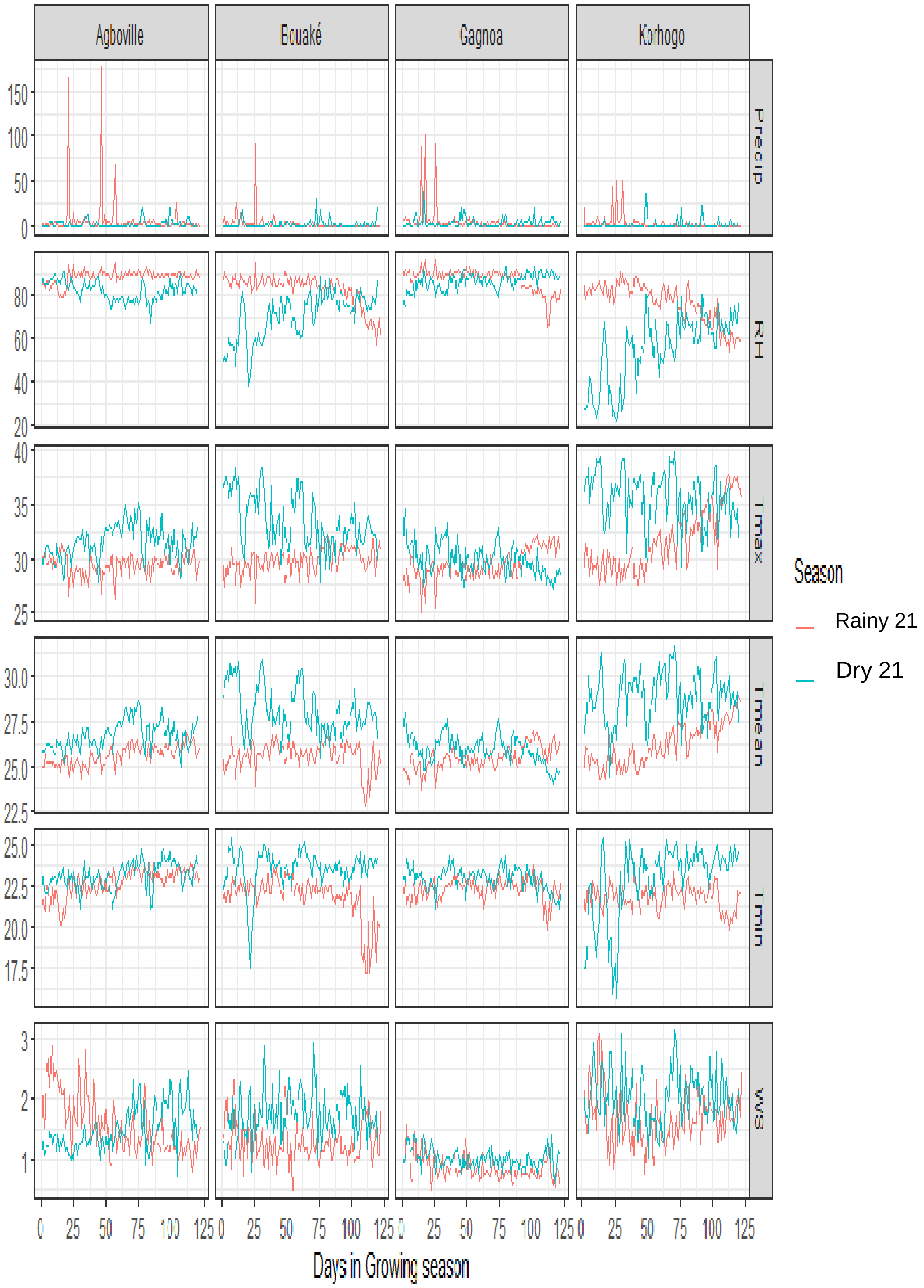

Fig. 1. Daily variation of Rainfall (Precip); Relative humidity (RH); Maximum (Tmax); Mean (Tmean) and Minimum temperature (Tmin) with Wind speed (WS) during dry (blue line) and rainy seasons (red line) of 2021 in different studied areas
Precip in mm; RH in %; Tmax,Tmean and Tmin in ^{0}C with WS in m/s

Table 5. Soil characterictics of different areas

Variables	Study areas				Significance
	Agboville	Bouaké	Gagnoa	Korhogo	p-value
pH $_{Water}$	6.6^a	6.7^a	6.7^a	6.3^b	**
pH $_{KCl}$	6.3^a	6.3^a	6.3^a	6^b	**
∆ Ph	0.3	0.4	0.4	0.3	-
Si (cmol.kg^{-1})	2,22^{ab}	2.13^b	2,28^a	1,94^c	**

*Different letters indicate significant differences between mean values within comparison done with Kruskal-Wallis with Dunn's test at ** p < .001*

3.3 BS Trough Rice Cropping Seasons

Average BS severity varied significantly across the studied areas, with the highest severity in Agboville and the lowest in Korhogo. Seasonal variability was observed, with higher severities during the rainy season. Altitudinal decreasing of BS severity was observed as illustrated in Fig. 2, with the highest occurrence in the forest zone and the lowest in the savanna, regardless of the season.

3.4 BS with Climatic Parameters

Meteorological parameters, especially RH and rainfall, strongly influenced the severity of BS in rice. The correlation between BS severity and climate parameters is shown in Table 8. RH and rainfall were positively correlated with BS severity, while Tmax and Tmean with WS were correlated negatively. Minimum temperature had no significant effect.

Backward regression identified Maximum and Mean temperature as significant variables affecting BS severity occurrence, with Rainfall initially identified. These parameters can predict severity with 56% accuracy. According to Fig. 3 presenting correlation between soil and environmental factors, rainfall was closely related to maximum temperature and then had been removed from the model, decreasing R^2 to 48% with low RMSE and MAE. Thus, the regression model developed is indicated in the following equation:

$$\text{Severity} = 1.44\ \text{Tmean} - 1.13\ \text{Tmax} \tag{4}$$

$$R^2 = 0.48$$

3.5 BS with Soil Properties

Lowland rice cultivation's BS is affected by soil pH_{Water}, pH_{KCl}, and SiO_2 content (Table 9), positively correlated to its progress. BS has negative effects on grain yield (R = -0.43) by reducing paddy. SiO_2 rate in soil was found as the main predictor for recorded BS severity at 17% through regression analysis. The linear equation was as follows:

$$\text{Severity} = 9.70\ \text{e-4}\ SiO_2 \tag{5}$$

$$R^2 = 0.17$$

Table 6. BS severities through seasons

	Brown Spot severity	
	Dry Season	Rainy Season
Agboville	4.29±1,20	3,32±0.67
Bouaké	2.52±0.82	2.96±0.75
Gagnoa	3.22±1.35	3.48±1.06
Korhogo	1.06±0.36	1.62±0.56

Data presented are the means ± standard deviations (Sds) for different regions

3.6 BS with Soil and Climate

From regression analysis, three (Relative humidity, Rainfall, and Wind speed) of the six significant predictors for BS were removed due to strong correlation with Maximum temperature (Fig. 3). The final regression equation used three variables (Total SiO^2, pH KCl, and Maximum temperature) and had an R^2 value of 53%. Thus, the regression equation obtained is presented as follows:

$$\text{Severity} = 1.42\ \text{pH KCl} + 5.04\text{e-4}\ SiO_2 - 0.24\ \text{Tmax} \tag{6}$$

$$R^2 = 0.53$$

3.7 Rice Yield and Effects of Season and/ or Site on Yield

Average paddy yields ranged from 4.5 to 6.5 t.ha-1 with the highest yield at Korhogo, followed by Bouaké and Agboville, and the lowest at Gagnoa as presented by Fig. 2 considering both seasons. Yield varied significantly across sites and seasons, with Korhogo consistently producing the highest yields and Gagnoa the lowest. Dry season yields were significantly higher than rainy season yields (*P < .05*) (Table 10).

3.8 Rice Yield and Climate Parameters

From results Temperature (Mean, Maximum, and Minimum) and Wind speed positively affected rice yield during the growing season, while high humidity (rainfall and relative humidity) decreased yield (p < .05) (Table 11). Five climate parameters including Minimum and Mean temperature, Relative humidity, Wind speed and Rainfall were found to be significant predictors of rice paddy yield. These parameters can predict rice yield with 43% accuracy and low RMSE and MAE. Due to collinearity with relative humidity, Rainfall, wind speed and mean temperature were removed (Fig. 3). The regression model is presented as follows based on low correlation between Minimum temperature and Relative humidity:

$$\text{Yield} = 0.46\ \text{Tmin} – 6.02.\ 10\text{-}2\ \text{RH} \qquad (7)$$

R^2= 0.37

3.9 Rice Yield and Soil Parameters

Silicon content and acidity of soil impacted significantly rice grain yield obtained as presented in Table 11. Those parameters affected negatively rice grain yield as expressed soil pHwater (-0.35), pHKCl (-0.22) and soil content of SiO_2 (-0.15).

3.10 Rice Yield with Soil and Climate Parameters

The best variables describing the yield of rice with the lowest AIC (21.21%) were Maximum and Minimum temperature, Rainfall, Wind speed, and Relative humidity. However, Relative humidity, Rainfall, Wind speed, and Maximum temperature were highly correlated. When they were associated separately with Minimum temperature, which appeared as the main predictor, the R^2 value dropped to 0.37 except for Rainfall (0.27). Eq. 8 was presented as the best predictor of rice grain yield.

$$\text{Yield} = -\ 6.02\ 10^{-2}\ \text{RH} + 0.46\ \text{Tmin} \qquad (8)$$

R^2= 0.37

Table 7. ANOVA table summarizing effects of seasons and sites on BS occurrence and rice yield

Source	DF	Sum of Squares	Mean Square	F ratio	Pr(>F)
			Brown Spot severity		
Season	1	5.82	5.82	10.452	0.00146
Site	3	154.65	51.55	92.648	< 2e-16
Interaction	3	13.62	4.54	8.162	4.03e-05
Residuals	178	99.04	0.56		
Total	185	273,13			
			Rice paddy yield		
Season	1	56.66	56.66	54.021	8.11e-12
Site	3	80.95	26.98	25.728	9.26e-14
Interaction	3	13.16	4.39	4.181	0.00693
Residuals	169	177.26	1.05		
Total	176	328,03			

Table 8. Correlation between climate parameters and BS severity

Climatic parameters	Brown Spot Severity	
	R	**P-value**
Tmax **	-0.58	< 2.2e-16
Tmin	0.10	0.1608
Tmean **	-0.49	1.1e-12
Rainfall **	0.38	7.2e-08
Relative humidity **	0.66	<2.2e-16
Wind speed **	-0.42	1.90e-09

*** Variable affected significantly Brown spot severity*

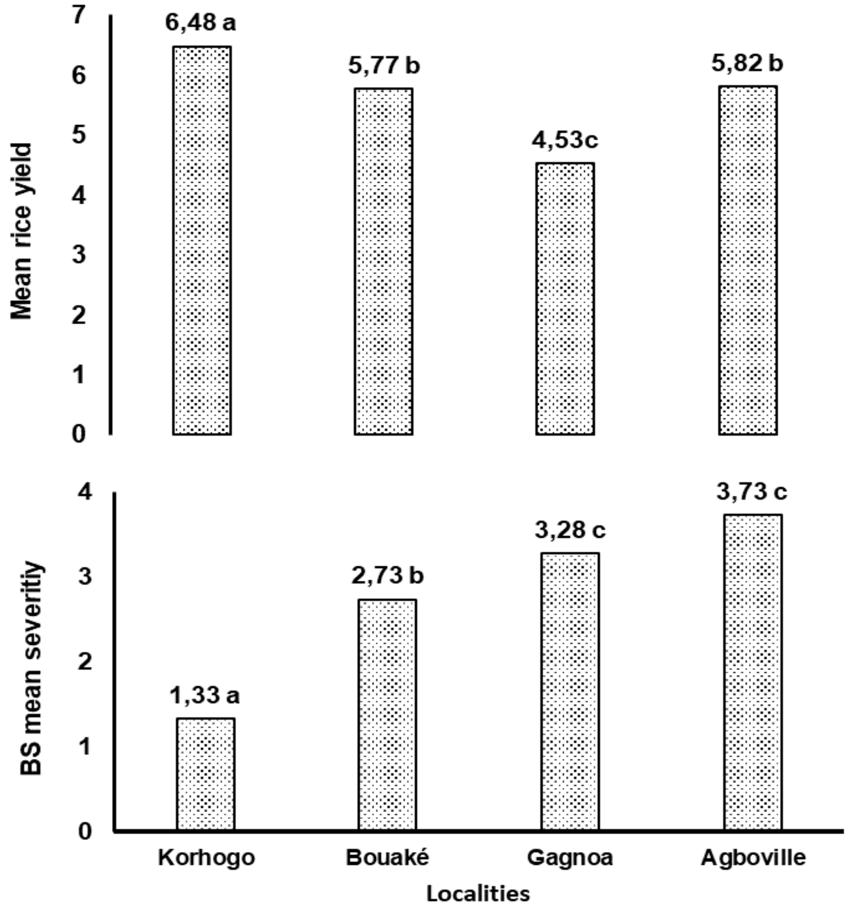

Fig. 2. Average rice yield in t.ha^{-1} (up) and rice brown spot severities (down) in different areas
Different letters indicate significant differences between mean values within comparison done with Kruskal-Wallis with Dunn's test

Table 9. Correlation between BS severity, soil properties and rice grain yield

Soil parameters	**Brown spot Severity**	
	R	**P-value**
pH_{Water} **	0.44	1.49e^{-10}
pH_{Kcl} **	0.52	2.58e^{-14}
ΔpH	-0.05	0.44
SiO_2 **	0.40	1.20e^{-8}
Yield	-0.43	1.44e^{-09}

*** Variable affected significantly Brown spot severity*

Table 10. Rice yield for different areas

Cropping seasons	**Yield (t/ha)**			
	Agboville	**Bouaké**	**Gagnoa**	**Korhogo**
Dry Season	6.45±1.50	6.51±0.48	4.58±0.99	7.09±1.48
Rainy Season	5.58±0.96	5.03±0.84	4.51±0.70	5.87±1.09

Data presented are the means ± standard deviations (Sds) for different regions

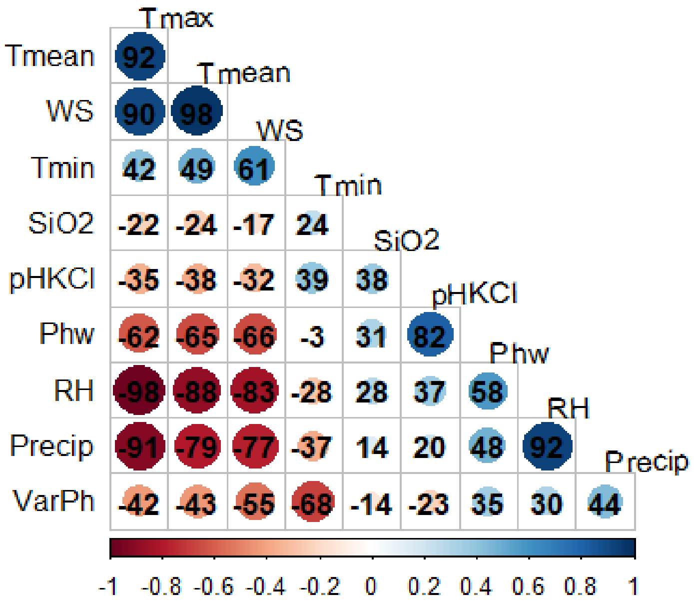

Fig. 3. The correlationships of soil parameters with environmental factors

Correlations are displayed in blue (positive) and red (negative); color intensity is proportional to the correlation coefficient. Tmean; Tmin; Tmax; WS; SiO2; pHKCl; PhW; RH; Precip and VarPh represent mean, minimum; maximum temperature; wind speed, silicon content; soil actual and potential acidity, relative humidity, rainfall and variation between soil acidity

4. DISCUSSION

4.1 Rice Production across Brown Spots Occurrence Agro-ecology

Soil conditions influence plant growth thereby the expression of many important traits, especially grain yield. Soil pH values between 6.0 and 7.0 are considered neutral whereby most plant nutrients remain available [26]. In this study, the actual soil acidity (soil pHwater) from savanna to forest zone ranged from 6.3 to 6.7, neutral values suitable for soil micronutrient availability [27]. Similarly, silicon increased from the savanna zone to the forest zone, ranging from 1.94 to 2.22 cmol.kg-1 respectively, reflecting the positive correlation between soil silicon and acidity (R = 0.38) [28]. The practical importance of that correlation is maintaining optimal soil pH level is crucial for achieving high rice yields, as silicon plays a significant role in the growth and defense system against fungal attacks and other biotic stresses [18,29]. However, at sites with the same soil pH, rice yields varied (5.8 t. ha-1 and 4.5 t. ha-1 respectively at Bouaké and Gagnoa) despite similar BS scores (3) due to differences in silicon availability and utilization, indicating the importance of maintaining soil conditions that favor silicon availability. Therefore, when soil conditions favor silicon availability, silicon release for crop use remains dependent on soil temperature, soil pH, and redox potential, which is affected by weathering rates. In tropical soils, silicon release is generally low due to high weathering, mostly in rice soils [28]. High levels of precipitation in the forest zone may decrease the release of silicon for rice cultivation use, thereby increasing the susceptibility of rice to BS pathogens. Haynes & Zhou [30] and Vander Linden & Delvaux [31] reported in tropical rice soils that extractable silicon decreases with increasing precipitation and weathering, highlighting the interaction between weather variations and nutrient availability in the soil.

High temperatures reduce BS pressure in the fields with the availability of nutrients that interact better with the released Si enhances and promotes better growth of rice plants for good yield [32]. In the savanna zone, the combination of rainfall and high temperatures led to Si availability, reduced BS pressure, and mobilization of nutrients such as phosphorus, iron associated with soil organic matter, resulting in a yield of around 6.5 t/ha. Higher humidity in the forest zone led to BS occurrence in both rainy and dry seasons, preventing rice plants from effectively absorbing nutrients and resulting in lower yields despite the high Si content of the soil, which also had lower fertility [33]. Another nutrient contributing to the observed difference in grain yield between sites was the soil potassium content, which was low (0.008 - 0.02 cmol/kg) compared to the optimal levels of 0.10 and 0.213 cmol/kg defined respesctively by [34,35] for rice nutrition. This implies that potassium (K) is a key soil component to support the effect of silicon in controlling the occurrence and yield of BS.

Temperature and humidity, which are part of ecological variance, have been shown to impact rice plant growth under various diseases such as bacterial blight and sheath blight pressure in several studies [36,37]. Temperature, precipitation and soil conditions are the primary determinants of crop growth and yield, confirming decrease in rice yield observed from the hot savanna zone to the humid forest zone along the altitudinal gradient [33,38]. High humidity and low temperatures increase the prevalence of rice brown spot disease, which is seed-borne. Conversely, maximum temperature and wind speed negatively impact its occurrence (R= -0.58 and R= -0.42 respectively) [13,39]. Grain yield was negatively affected by high levels of rainfall and relative humidity, which have a strong positive relationship with air temperature [40,41]. Lower temperatures increase fungal pathogens' prevalence and reduce it outside the optimal range. Managing environmental factors is necessary to prevent crop damage, as disease occurrence negatively affects rice grain yield.

This study found that weather and soil conditions are important factors in the occurrence of BS in Côte d'Ivoire, with regression models predicting over 50% of BS occurrence. However, the variation of the reaction among the rice varieties grown by farmers in the surveyed areas needs to be further explored for additional insights.

4.2 BS Control by Silicon

The surveyed sites were found to have Si levels ranging from 1.94 to 2.28 cmol/kg and potential Si content per hectare ranging from 1717 to 2035 kg Si/ha, exceeding the recommended rate of 1000 kg Si/ha to increase soil pH by 0.29-0.47 units in all soils [42] leading no significant variation in pH. The pH only rose by 0.4 units between Bouaké and Korhogo for a difference of 0.19 cmol Si/kg and by 0.1 units between Agboville and Gagnoa for a difference of 0.06 cmol Si/kg. Moreover, the Si content of surveyed soils (0.859 mg.dm-3 - 1.02 mg.dm-3) was much lower than the required critical concentration of 10-20 mg.dm-3 for achieving maximum yield with low BS occurrence in rice crops [43]. This may have contributed to the increase in BS occurrence (R = 0.40) and the reduction in rice grain yield (R = -0.15) observed in this study. Available Si can substitute C in shoot tissues, increase photosynthesis, and strengthen C:N:P stoichiometry leading to enhanced biomass production through N and P uptake. It also provides bioenergetic benefits due to altered C:N stoichiometry, particularly in low N conditions as varieties with high N responsiveness were found to be less susceptible to BS [9,44]. Si uptake indirectly promotes the absorption of other nutrients for plant physiological and BS resistance independently of classic immune hormones like salicylic and jasmonic acid during BS attack [45]. More research is needed to understand the relationship between silicon and other soil metabolites and their effects on rice plants to develop effective approaches for controlling brown spot disease.

Table 11. Correlation between rice yield, temperature, rainfall, and relative humidity

		Yield	
		Coeff Corr	**P-value**
Weather parameters	Tmax	0.63	< 2.2e-16
	Tmean	0.62	< 2.2e-16
	Tmin	0.33	5.81e-06
	Rainfall	-0.43	2.76e-09
	Relative humidity	-0.60	< 2.2e-16
	Wind speed	0.62	< 2.2e-16
Soil parameters	pH_{Water}	-0.35	1.66 e-6
	pH_{KCl}	-0.22	3.46 e-3
	ΔpH	-0.24	1 e-3
	SiO_2	-0.15	0.04

Considering multiple regression, contribution of Si was positive but lowest (R=0.40), which was unexpected based on previous studies [7] that suggested a negative coefficient. We hypothesized a polynomial relationship between soil Si content and BS occurrence, taking into account soil pH, rainfall, minimum temperature, and relative humidity, where higher Si levels would reduce BS occurrence. However, we found that Si had limited effectiveness in controlling BS, as the optimal rate for limiting iron toxicity in rice was only 371 kg Si/ha [17]. Max temperature significantly contributed to BS occurrence during the crop season, indicating rice susceptibility to injury under projected temperature increases (by 99.5% of current value) and reduced rainfall amount [46]. Furthermore, Regression analysis showed that soil pH, Si concentration, and maximum temperature were significant predictors of BS occurrence.

5. CONCLUSION

Interaction of weather and soil can have significant impact on BS occurrence and rice yield depending of the agro-climatical zone in Côte d'Ivoire as revealed this study. Zones with high temperature and wind speed decreased BS pressure, promoting the final rice yield. In addition, soil pH and high levels of Si when they are associated to more humidity conditions increased BS across studied areas. Therefore, further research should take a comprehensive approach based on this complex interaction including cultural practices, and varietal selection in order to reduce the impact BS for better rice production in future.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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