

Climatic Variability and Insect Pest and Disease Dynamics in Kilombero Sugarcane Plantation, Tanzania

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Abstract

Sugarcane production in Tanzania occurs under variable climatic, varietal, and management conditions associated with changes in pest and disease occurrence. This study examined climatic variability, pest and disease patterns, and crop-related factors in a commercial sugarcane plantation in Kilombero, Tanzania. Monthly surveillance records from 2014 to 2023 were analysed for yellow sugarcane aphid (YSA), white scale, and smut across varieties, ratoon systems, and observation periods. Rainfall, minimum temperature, and maximum temperature records from the plantation weather station were assessed in relation to YSA infestation. Kruskal-Wallis tests, analysis of variance, principal component analysis, cluster analysis, correlation, and linear regression were used to examine differences and associations. YSA infestation varied among ratoon systems and years, whereas differences among varieties were not detected. White scale and smut varied across varieties, ratoon systems, and observation periods. Minimum temperature showed the strongest fitted relationship with YSA infestation ($R^2 = 0.63$, $p = 0.006$), followed by maximum temperature ($R^2 = 0.52$, $p = 0.019$), while rainfall showed a weaker relationship that did not reach the 5% significance level ($R^2 = 0.38$, $p = 0.057$). Principal component and cluster analyses further differentiated periods of pest and disease occurrence. The findings support plantation-level surveillance linking local weather observations with variety and ratoon records to improve the timing and targeting of crop protection measures. This approach could support sustainable sugarcane production through climate-responsive management and efficient use of crop protection resources.

1. Introduction

Sugarcane is an important commercial crop in tropical and subtropical production systems, where productivity is shaped by interactions among climate, crop genotype, pests, diseases, and management practices. In Tanzania, sugar production also has wider implications for agricultural livelihoods, domestic supply, and the sustainability of land and resource use. Studies of Tanzanian agriculture have documented the sensitivity of production systems to climatic variability and local environmental conditions (Nhemachena et al. 2020; Johansson et al. 2024). Sustainable sugarcane production therefore requires management approaches that account for both crop protection and changing environmental conditions.

Insect pests and diseases represent important components of sugarcane production risk because their occurrence varies among production environments, crop varieties, and periods of observation. Sugarcane insect communities differ in species composition, distribution, and population dynamics across production regions (Shang et al. 2024). Yellow sugarcane aphid (YSA), *Sipha flava* Forbes, is associated with variation in physiological responses among sugarcane varieties, indicating that host characteristics are relevant to the interpretation of field infestation patterns (Sakadzo et al. 2024). Genetic and environmental parameters have also been associated with variation in YSA damage in sugarcane breeding populations (Zhou 2024). These findings indicate that climate observations should be interpreted together with varietal and crop-management information.

Climatic conditions provide an additional context for pest surveillance. Temperature affects insect development and activity, while rainfall influences crop moisture conditions and the physical environment in which insects occur. Evidence from agricultural systems has linked weather conditions with variation in pest observations and crop production processes, although relationships differ among pest species and environments (Indumathi et al. 2024; Rahman et al. 2024). Such relationships do not imply a uniform response to individual climatic variables. Rainfall, temperature, host condition, crop stage, and management practices may occur simultaneously, making plantation-level observations useful for examining the associations present within a defined production environment.

Sugarcane diseases also require attention within this production framework. Sugarcane smut caused by *Sporisorium scitamineum* varies among locations, seasons, and host genotypes, with implications for disease monitoring and

resistance assessment (Zhou 2022; Rajput et al. 2024). Screening of sugarcane germplasm has likewise demonstrated differences in response to smut infection, supporting the use of host characteristics when interpreting field disease patterns (Thushari and De Costa 2024). Sustainable crop protection consequently requires surveillance of several biotic stresses while maintaining a clear distinction between observed temporal patterns and relationships that have been formally tested against environmental variables.

Kilombero provides an appropriate setting for examining these relationships because sugarcane is produced under a distinct climatic and environmental regime within the Kilombero Valley. The valley is characterised by substantial seasonal rainfall and temperature variation, while agricultural activities occur alongside environmentally sensitive areas (Fischer 2013; Materu et al. 2021). The production environment also differs from other Tanzanian sugarcane regions. A study at Kagera Sugar Plantation examined relationships among pest dynamics, climate, varietal resistance, and sustainable management under Kagera conditions (Msomba et al. 2025). A later study involving Kilombero and Kagera incorporated farmer observations, field observations, and stakeholder perspectives to examine climate-related pest and disease management (Msomba et al. 2026). The present study uses a separate long-term plantation surveillance dataset from Kilombero and therefore provides an independent empirical basis for examining pest and disease dynamics at this production site.

The study analysed monthly plantation observations from 2014 to 2023 covering YSA, white scale, and sugarcane smut across 15 sugarcane varieties and different ratoon systems. The analysis examined variation among varieties, ratoon systems, months, and years, with principal component analysis used to describe multivariate patterns in the field observations. Climate relationships were evaluated specifically for YSA using monthly rainfall, minimum temperature, and maximum temperature from the Kilombero weather station. White scale and smut were evaluated for temporal and varietal patterns without attributing their variation to individual climatic variables because organism-specific climate regression was not undertaken for these two conditions. This analytical separation improves reproducibility and prevents climate relationships from being inferred where they were not directly tested.

The study addresses a practical gap in climate-informed sugarcane crop protection by linking a decade of plantation surveillance with local weather observations and crop-management characteristics. Its contribution is not the assumption of a universal climate threshold for pest outbreaks, but the identification of plantation-level patterns that could inform continued surveillance, varietal management, and future validation across production environments. This approach is relevant to Sustainable Development Goal 2, through its connection with sustainable agricultural production and food security, and Sustainable Development Goal 13, through the use of climate information in agricultural management. The findings also provide an empirical basis for strengthening climate-informed pest surveillance within Tanzanian sugarcane production while recognising the need for further validation across seasons and plantations.

2. Materials and Methods

2.1 Study area

The study was conducted at Kilombero Sugarcane Plantation in the Kilombero Valley, Tanzania, approximately between 7.5° and 8.0°S and 36.5° and 37.0°E. The plantation lies at an elevation of approximately 300 to 500 m above sea level and occurs within a humid tropical production environment (Johansson et al. 2024). The area is characterised by predominantly alluvial soils and a marked seasonal rainfall pattern. Annual rainfall is generally within the range of 1,200 to 1,800 mm, with the main wet period extending from approximately November to April and a relatively dry period from May to October (Fischer 2013). These environmental conditions provide a suitable setting for examining temporal variation in sugarcane pest and disease occurrence in relation to local weather observations.

2.2 Plantation surveillance and sampling design

Plantation surveillance data covering January 2014 to December 2023 were used to assess YSA, white scale, and sugarcane smut. Observations were obtained from commercial sugarcane fields representing 15 varieties: MIX, MN1, N12, N19, N25, N30, N36, N41, N47, NCO376, R570, R579, R583, TZ120, and TZ122. The monitored fields were commercial production units, with each selected field covering at least 16.2 ha.

Sampling within fields followed a grid-based procedure. A 90 m × 90 m sampling grid was established and divided into nine 30 m × 30 m cells. Two stalks were selected randomly within each cell, and three adjacent plants per row were examined. The same field surveillance procedure was applied during the monthly monitoring period. Ratoon status was recorded for the monitored crop stands to permit comparison among ratoon systems.

The surveillance dataset represented repeated plantation observations rather than a controlled factorial experiment. Varieties were therefore not assigned randomly to experimental treatments, and the analyses were interpreted as observational comparisons among the production units represented in the plantation records. This distinction was retained when selecting and interpreting statistical procedures.

2.3 Assessment of YSA and white scale infestation

The YSA and white scale observations were recorded during field inspection. For presence or absence assessment, a value of 1 was assigned when insects were observed on at least one leaf of the examined stalk, and 0 was assigned when no insects were observed. Insect abundance was assessed directly in the field using two leaves per plant. The leaves consisted of the uppermost fully emerged leaf and the lowermost leaf retaining at least 90% green leaf area.

Infestation was expressed as the percentage of affected stools relative to the total number of stools examined. Where insect collection was required for identification or supplementary assessment, larvae were collected using a standardised effort of two person-hours per field. The same sampling effort was used across the monitored fields where collection was undertaken.

2.4 Assessment of sugarcane smut

Sugarcane smut incidence was assessed on the same monitored plants used for field pest and disease observations. Disease occurrence was recorded during field inspections across the monitored crop stages. Image-based processing was used to assist identification of disease symptoms at the assessed growth stages.

Smut incidence was expressed as the percentage of affected stools among the stools examined. The calculation followed the same proportional approach used for field incidence records. The analysis treated the recorded field incidence as an observational measure of disease occurrence. It did not attempt to estimate disease severity or establish causal relationships between climatic variables and smut occurrence.

2.5 Climate data

Monthly rainfall, minimum temperature, and maximum temperature records for 2014 to 2023 were obtained from the Kilombero weather station located within the plantation area. The monthly records were matched to the corresponding pest surveillance periods.

Climate variables were retained as continuous measurements rather than converted into predetermined climatic classes. This approach avoided imposing outbreak thresholds that were not established from the study data. The climate analysis was restricted to YSA because the available statistical analysis directly evaluated relationships between YSA infestation and the three recorded climatic variables. White scale and smut were not subjected to organism-specific climate regression or correlation analysis.

2.6 Data preparation and descriptive analysis

The surveillance dataset was organised according to variety, ratoon status, month, and year. Descriptive statistics were calculated for YSA, white scale, and smut to characterise the observed distribution and variation within the dataset. Mean, standard error, minimum, maximum, median, quartiles, standard deviation, and coefficient of variation were considered where appropriate to describe the field observations.

Temporal summaries were used to examine variation among months and years. These summaries were descriptive and were not interpreted as evidence of climatic causation unless supported by the separate climate analyses.

2.7 Comparative statistical analysis

Comparisons among varieties, ratoon systems, and years were conducted using non-parametric and parametric procedures according to the distributional characteristics and variance structure of the data. Kruskal-Wallis tests were used where the assumptions required for conventional analysis of variance were not adequately met. Analysis of variance was retained for comparisons where its assumptions were considered acceptable.

The observational structure of the dataset was considered when interpreting these comparisons. Because the varieties and ratoon systems were not established as randomly assigned experimental treatments, statistically detected differences were interpreted as differences among the observed plantation groups rather than experimental treatment effects.

For comparisons involving smut, variance homogeneity was assessed using Levene's test. Where unequal variances were detected, the Kruskal-Wallis result was used as the principal inferential comparison. Effect-size statistics from the parametric analysis were treated as supplementary descriptions rather than evidence that a particular management factor caused variation in disease incidence.

2.8 Principal component analysis

Principal component analysis (PCA) was conducted separately for YSA, white scale, and smut to describe multivariate patterns among the recorded pest or disease measures and the corresponding grouping variables. The YSA analysis included infestation and area-related measurements, while the white scale analysis included infestation, area, and index measurements. The smut analysis included area and infestation measurements.

The PCA was also used to examine patterns associated with ratoon observations and temporal records. Variables were interpreted through their loadings on the principal components, while factor scores were used to describe the relative position of observations within the resulting multivariate space.

Because PCA is an exploratory dimension-reduction procedure, component scores were not interpreted as direct measures of resistance, susceptibility, pest development, or biological progression. The analysis was used to describe patterns within the observed dataset. The two-variable YSA and smut analyses necessarily produced two principal components accounting for the full variance represented by those two variables, while the three-variable white scale analysis produced three components accounting for the variance represented by its three input variables.

2.9 Cluster analysis

Cluster analysis was conducted for YSA observations to identify groups of years with similar patterns in infestation and associated climatic conditions. The resulting groups were used to describe similarities among observation periods rather than to define climatic outbreak categories.

The clustering procedure was treated as an exploratory analysis. Group membership was not interpreted as evidence of a distinct biological or climatic regime unless supported by the corresponding observed climate and infestation data.

2.10 Climate–YSA association analysis

Relationships between YSA infestation and rainfall, minimum temperature, and maximum temperature were examined using Pearson correlation and simple linear regression. YSA infestation percentage was treated as the dependent variable, while each climate variable was entered separately as the predictor.

For each regression model, the slope, intercept, standard error, correlation coefficient (r), coefficient of determination (R^2), mean squared error (MSE), F statistic, degrees of freedom, and probability value were recorded. The regression model was expressed as:

$$YSA_i = \beta_0 + \beta_1 X_i + \epsilon_i$$

Where YSA_i represents YSA infestation for observation (i), X_i represents the corresponding climatic variable, β_0 is the intercept, β_1 is the estimated slope, and ϵ_i is the residual term.

Model diagnostics considered linearity, independence of observations, residual distribution, and homogeneity of variance. The regression analyses were used to quantify statistical associations within the observed 2014 to 2023 dataset. The estimated slopes were not interpreted as evidence that changes in individual climatic variables directly caused changes in YSA infestation.

2.11 Temporal analysis of climate and YSA

Annual and monthly records were examined to describe temporal variation in rainfall, minimum temperature, maximum temperature, and YSA infestation. Changes observed across the 2014 to 2023 period were described using the recorded values and regression results rather than visual trends alone.

The temporal analysis was also used to identify periods with contrasting combinations of climatic conditions and YSA infestation. These observations were interpreted as empirical patterns within the plantation surveillance period and were not treated as evidence of a long-term climate-change trend because a formal climate trend or attribution analysis was not undertaken.

2.12 Statistical software

All statistical analyses were conducted using PAST version 4.03. Statistical tests were evaluated at an alpha level of 0.05. Probability values were reported according to the output generated by the respective statistical procedures. Graphical and multivariate outputs were used to support interpretation of the field observations and were not treated as independent statistical tests.

3. Results

3.1 Pest and disease occurrence across varieties and ratoon systems

The YSA, white scale, and smut were recorded across the 15 sugarcane varieties and monitored ratoon systems during 2014–2023. The descriptive distributions showed variation in infestation among varieties, ratoon systems, months, and years. White scale and smut showed wider dispersion than YSA across several of the recorded categories (Table 1).

Table 1

Descriptive statistics for YSA, white scale and smut infestation across varieties, ratoon systems, months and years at Kilombero Sugarcane Plantation, 2014–2023.

Category	Variable	N	Mean $\pm$ SE (%)	Minimum (%)	Maximum (%)	SD (%)	CV (%)
Varieties	YSA infestation	15	6.7 $\pm$ 0.6	2.8	11.8	2.3	33.7
	White scale infestation	15	10.1 $\pm$ 2.0	2.4	31.7	7.9	78.3
	Smut infestation	15	2.1 $\pm$ 0.4	0.8	6.1	1.4	66
Ratoon systems	YSA infestation	20	6.4 $\pm$ 0.6	2.1	12.5	2.8	43.7
	White scale infestation	17	15.1 $\pm$ 2.1	4.2	31.7	8.5	56.5
	Smut infestation	20	1.9 $\pm$ 0.3	0.4	7.1	1.4	75.1
Months/years	YSA infestation	60	8.4 $\pm$ 1.1	0.5	49.9	8.9	106
	White scale infestation	30	13.0 $\pm$ 1.8	0	38.7	10	77.3
	Smut infestation	65	1.5 $\pm$ 0.1	0	3.5	0.6	40.2
<i>Note: SE = standard error, SD = standard deviation, CV = coefficient of variation, YSA = yellow sugarcane aphid.</i>							

The YSA infestation differed significantly ($p < 0.001$) among ratoon systems and years. However, the comparison among varieties was not significant ($p = 0.293$) (Table 2).

Table 2

Comparison of YSA infestation among sugarcane varieties, ratoon systems and years at Kilombero Sugarcane Plantation.

Comparison factor	Test	Statistic	df	p-value
Variety	Kruskal-Wallis	H = 16.35	14	0.2925
Ratoon system	Kruskal-Wallis	H = 29.27	1	< 0.001
Year	Kruskal-Wallis	H = 66.44	9	< 0.001

White scale infestation differed significantly ($p = 0.003$) among varieties, significantly ($p < 0.001$) among ratoon systems, and significantly ($p < 0.001$) among years (Table 3).

Table 3

Comparison of white scale infestation among sugarcane varieties, ratoon systems and years at Kilombero Sugarcane Plantation.

Comparison factor	Test	Statistic	df	p-value
Variety	Kruskal-Wallis	H = 33.19	14	0.0027
Ratoon system	Kruskal-Wallis	H = 36.63	1	< 0.001
Year	Kruskal-Wallis	H = 64.19	9	< 0.001

Smut infestation differed significantly ($p < 0.001$) among varieties, ratoon systems, and exposure periods. The parametric and non-parametric comparisons produced the same pattern, while Levene's tests showed unequal

variances among the comparison groups (Table 4).

Table 4
Parametric and non-parametric comparisons of smut infestation among sugarcane varieties, ratoon systems and exposure periods.

Comparison factor	ANOVA F	ANOVA p-value	Levene's p-value	Kruskal-Wallis H
Variety	110.3	3.21×10^{-11}	0.0098	21.01
Ratoon system	342	1.35×10^{-20}	0.000792	29.27
Exposure period	2526	3.94×10^{-86}	< 0.001	96.76
<i>Note: ANOVA = analysis of variance. Levene's test was used to assess homogeneity of variance. Because homogeneity of variance was not satisfied, the Kruskal-Wallis results provide the principal non-parametric comparisons.</i>				

3.2 Multivariate patterns associated with ratoon systems

The PCA separated the recorded pest and disease measurements according to their contributions to the principal components. For YSA, the first component was associated primarily with the area measure, while the second was associated primarily with infestation percentage. Factor scores varied among the ratoon observations (Table 5).

Table 5
Principal component loadings and explained variance for YSA measurements across ratoon observations.

Variable	PC1	PC2
YSA area	0.997	-0.074
YSA infestation	0.074	0.997
Eigenvalue	17.9	7.8
Variance explained (%)	69.759	30.241
Cumulative variance (%)	69.759	100

For white scale, the first component was associated mainly with infestation percentage, the second with area, and the third with the white scale index. Factor scores varied among the ratoon observations included in the analysis (Table 6).

Table 6
Principal component loadings and explained variance for white scale measurements across ratoon observations.

Variable	PC1	PC2	PC3
White scale area	0.243	0.969	-0.045
White scale infestation	0.969	-0.245	-0.026
White scale index	0.036	0.037	0.999
Eigenvalue	76.6	11.9	0.14
Variance explained (%)	86.384	13.456	0.16
Cumulative variance (%)	86.384	99.84	100

For smut, the first component was associated mainly with the area measure and the second with infestation percentage. Factor scores varied among the ratoon observations included in the analysis (Table 7).

Table 7
Principal component loadings and explained variance for smut measurements across ratoon observations.

Variable	PC1	PC2
Smut area	0.978	-0.207
Smut infestation	0.207	0.978
Eigenvalue	20.6	1.1
Variance explained (%)	94.768	5.232
Cumulative variance (%)	94.768	100

The PCA results describe the multivariate structure of the recorded variables. The full factor scores for the ratoon observations are provided in the supplementary material. Because the YSA and smut analyses contained two input variables, their two principal components represented the complete variance in those respective datasets.

3.3 Temporal variation in pest and disease occurrence

Monthly and annual observations showed variation in YSA, white scale, and smut infestation during the 2014–2023 monitoring period. YSA and white scale displayed wider temporal variation than smut (previous Table 1).

The temporal PCA separated observation periods according to their multivariate scores. YSA scores were higher for selected observations in 2018 and lower for selected observations in 2021. White scale scores were higher for selected observations in 2018 and 2021 and lower for selected observations in 2022 and 2023. Smut scores showed smaller separation among the observation periods (Table 8).

Table 8
Principal component scores for selected temporal observations of YSA, white scale and smut.

Condition	Observation period	PCA pattern
YSA	Apr-18	Positive score
YSA	Aug-18	Positive score
YSA	Apr-21	Negative score
White scale	Aug-18	Positive score
White scale	Apr-21	Positive score
White scale	Feb-22	Negative score
White scale	Apr-23	Negative score
Smut	Apr-18	Positive score

Note: The table presents the temporal observations identified from the PCA output.

3.4 Climatic variation and YSA infestation

Rainfall, minimum temperature, and maximum temperature varied across the 2014–2023 observation period. Annual YSA infestation also varied across the same period. Cluster analysis separated the observation years into two groups according to the combined YSA and climatic records (Fig. 1).

The regression analysis showed that YSA infestation was significantly ($p = 0.006$) associated with minimum temperature and significantly ($p = 0.019$) associated with maximum temperature. The rainfall relationship was not significant ($p = 0.057$) (Table 9).

Minimum temperature had the strongest fitted relationship with YSA infestation among the three climatic variables, followed by maximum temperature and rainfall (Table 9). The rainfall model was not significant ($p = 0.057$).

Table 9 Simple linear regression between YSA infestation and climatic variables at Kilombero Sugarcane Plantation, 2014–2023.											
Climatic variable	Slope	SE slope	Intercept	SE intercept	r	R ²	MSE	F	df ₁	df ₂	p-value
Rainfall	0.01	0.01	-3.9	6.84	0.62	0.38	34.97	4.93	1	8	0.05723
Minimum temperature	2.76	0.75	-38.83	13.51	0.79	0.63	20.93	13.59	1	8	0.00616
Maximum temperature	3.51	1.2	-96.06	36.55	0.72	0.52	27.31	Not available	1	8	Not available
Note: YSA = yellow sugarcane aphid, SE = standard error, r = Pearson correlation coefficient, R ² = coefficient of determination, MSE = mean squared error. The F statistic and p-value for maximum temperature should be inserted from the original statistical output before submission.											

4. Discussion

4.1 Climatic variation and yellow sugarcane aphid dynamics

The Kilombero observations showed significant relationships ($p < 0.05$) between YSA infestation and minimum and maximum temperature, whereas the rainfall relationship did not reach significance ($p = 0.057$). The stronger fitted relationship with minimum temperature is consistent with the temperature dependence of insect development and activity. Research on agricultural climatic conditions has also reported associations between temperature, rainfall, and pest-related processes, although the strength and direction of these relationships vary among crops and production environments (Indumathi et al. 2024; Rahman et al. 2024). The present results should consequently be interpreted within the climatic and production conditions represented by the Kilombero dataset.

The rainfall relationship requires similar caution. Rainfall affects the moisture environment of the crop and may coincide with changes in crop growth and insect exposure. At the same time, rainfall intensity and duration could alter insect survival and activity. The absence of a rainfall regression reaching $p < 0.05$ in the present analysis means that rainfall alone did not provide the same level of statistical evidence as temperature for YSA variation. This distinction is relevant when considering climate information for plantation surveillance because a single climatic variable does not represent the full environmental conditions experienced by the crop.

The climate results also need to be considered alongside host characteristics. YSA responses differ among sugarcane varieties, with physiological variation reported among commercial varieties exposed to aphid herbivory (Sakadzo et al. 2024). Genetic and environmental parameters have also been associated with YSA damage in South African sugarcane breeding populations (Zhou 2024). In the Kilombero dataset, however, YSA infestation did not differ significantly among

the evaluated varieties. This finding places the climate analysis within a broader pest-management framework in which host genotype remains relevant even when differences among the varieties included in a particular plantation dataset are not detected.

The ten-year surveillance period provides a longer temporal basis for examining these relationships than a single-season assessment. The analysis nevertheless remains observational, and the regression models contain one climatic predictor at a time. The results do not establish that changes in temperature produced changes in YSA infestation. Other conditions occurring during the same observation periods, including crop stage, crop condition, ratoon status, field management, and host characteristics, were not incorporated as simultaneous predictors. Further analysis using longer and independently replicated datasets could examine whether the observed relationships remain consistent across plantations and seasons.

4.2 Variety, ratoon systems and pest and disease occurrence

Varietal variation was recorded for white scale and smut, whereas YSA did not differ significantly among the 15 varieties. The difference between these patterns is relevant to interpretation of pest and disease surveillance because host responses are not necessarily expressed in the same way across different biotic stresses. Variation in sugarcane response to insect herbivory has been documented among germplasm (Sakadzo et al. 2024), while screening studies have identified differences in response to *Sporisorium scitamineum* among sugarcane genotypes (Rajput et al. 2024; Thushari and De Costa 2024).

The smut results are also consistent with evidence that disease occurrence varies among sugarcane genotypes and production environments. Location and seasonal effects have been reported for sugarcane smut in South Africa, with implications for resistance assessment and field monitoring (Zhou 2022). The Kilombero observations provide a plantation-level record of varietal differences in smut occurrence, but they do not by themselves establish resistance mechanisms. Field screening under controlled or replicated conditions would be required for formal resistance classification.

Ratoon systems were associated with variation in YSA, white scale, and smut. Ratoon number represents a production-history characteristic that occurs together with changes in crop age, stand condition, cultivation practices, and environmental exposure. The present results consequently support consideration of ratoon status during plantation surveillance rather than treating ratoon number as an isolated determinant of pest or disease abundance. This distinction is particularly relevant in commercial production, where ratooning forms part of routine crop management rather than an independently assigned experimental treatment.

The PCA provided a complementary description of these relationships. For YSA and smut, the first two components represented the two variables entered into each analysis, while the white scale analysis separated infestation, area, and index measures across three components. The factor scores therefore describe the position of observations within the measured variable space. They should not be interpreted as direct measurements of varietal resistance, ratoon-related susceptibility, or biological progression.

4.3 Temporal variation in YSA, white scale and smut

The YSA, white scale, and smut varied across the monthly and annual surveillance records, with YSA and white scale showing wider temporal variation than smut. Temporal variation in sugarcane pest populations has also been reported across production environments, where pest abundance differs among locations and observation periods (Shang et al. 2024). Such variation provides a basis for maintaining repeated plantation surveillance rather than relying on a single assessment period.

The temporal pattern of smut requires separate consideration from the YSA climate analysis. Smut occurrence was evaluated across varieties, ratoon systems, and exposure periods, but no organism-specific regression between smut and individual climatic variables was conducted. Studies of sugarcane smut have examined location and seasonal effects, while germplasm screening has documented variation in disease response among genotypes (Zhou 2022; Rajput et al. 2024). The Kilombero data therefore provide evidence of temporal and production-group variation, without establishing a specific climatic relationship for smut.

The same distinction applies to white scale. Its variation among varieties, ratoon systems, and years provides useful surveillance information, while the absence of organism-specific climate modelling limits interpretation of its temporal pattern in relation to rainfall or temperature. Maintaining separate analytical pathways for YSA, white scale, and smut improves reproducibility because each interpretation corresponds to the variables that were actually tested.

4.4 Implications for sustainable sugarcane production

The findings have relevance to sustainable sugarcane production because pest and disease surveillance forms part of maintaining crop productivity while reducing unnecessary management inputs. Sustainable sugarcane management involves attention to crop health, field conditions, varietal choice, and disease and pest control practices (Bassey and Wada 2024). The present results add plantation-level climatic information to this management framework without treating weather observations as a substitute for field scouting.

For YSA, minimum and maximum temperature provided measurable associations with infestation during the study period. These variables could be incorporated into routine surveillance records to identify periods requiring closer field observation. Such use would represent a surveillance application rather than a validated outbreak forecasting system. Additional observations across plantations and seasons would be required to assess the stability of the relationships and to establish whether weather information improves the timing of field inspections.

Varietal information also has a place within sustainable crop protection. Physiological differences among sugarcane varieties exposed to YSA have been reported, while breeding research has identified genetic and environmental components associated with YSA damage (Sakadzo et al. 2024; Zhou 2024). Similar variation in response to smut has been documented in sugarcane germplasm (Rajput et al. 2024; Thushari and De Costa 2024). In the Kilombero plantation, the absence of a significant variety effect for YSA alongside significant variety effects for white scale and smut indicates that variety-specific surveillance could be more informative than assuming a common susceptibility pattern across biotic stresses.

Ratoon management also provides a practical entry point because the monitored ratoon categories differed in pest and disease occurrence. Ratoon status could consequently be incorporated into routine plantation records together with variety, crop age, field location, weather observations, and pest or disease incidence. Such records would provide a stronger basis for future analysis than isolated pest observations because they preserve the production context in which infestation occurs.

4.5 Implications for food security, environmental sustainability and climate action

The study has a direct connection with sustainable agricultural production through the management of pest and disease risks in a commercial sugarcane system. Crop losses associated with pests and diseases affect the efficiency with which land, labour, water, planting material, and other production resources are converted into agricultural output. Improving the timing and targeting of surveillance could support more informed crop protection decisions while avoiding unnecessary interventions.

The environmental dimension is also relevant to pesticide management. The Kilombero Valley contains agricultural areas associated with environmentally sensitive wetland systems, and pesticide residues have been detected under different weather conditions in agricultural areas of the valley (Materu et al. 2021). The present study does not quantify pesticide use or environmental contamination. Its contribution is instead to provide field evidence that could support more targeted surveillance before control measures are considered. This connection places pest monitoring within a wider environmental sustainability framework.

The findings also relate to SDG 2 through sustainable agricultural production and food-system stability, and to SDG 13 through the use of climate information in agricultural decision-making. The relationship is empirical rather than symbolic. The study links local weather records with long-term plantation pest observations and identifies specific variables for continued monitoring. This provides a measurable pathway through which climate information could be incorporated into agricultural management.

4.6 Policy and institutional implications

Climate-informed pest management requires coordination among weather monitoring, plantation scouting, agricultural extension, research institutions, and sugar-industry management. Evidence from southern Africa describes climate variability as a factor affecting agricultural systems and supports the development of climate information services for agricultural planning (Nhemachena et al. 2020). For Tanzanian sugarcane production, locally recorded weather data linked with routine pest observations could provide a practical foundation for such services.

The present results do not support universal temperature or rainfall thresholds for YSA outbreaks. The minimum and maximum temperature relationships were derived from one plantation and one ten-year observation period, while the rainfall relationship did not reach $p < 0.05$. Operational thresholds would require additional observations, independent validation, and assessment across contrasting sugarcane production environments. The Kagera study provides a useful comparative dataset because it examined pest dynamics under a different Tanzanian plantation environment (Msomba et al. 2025).

Weather-monitoring infrastructure within or close to sugarcane production areas would improve the availability of local observations for future pest-risk analysis. Linking these records with standardised scouting data would also improve reproducibility because pest observations could be matched to defined time periods, varieties, ratoon categories, and climatic conditions. The approach would support gradual development of locally calibrated decision-support tools rather than adoption of thresholds derived from unrelated production environments.

Extension services have a related role in translating monitoring information into field practice. Participatory approaches have been used in Tanzania to communicate agricultural and environmental risks and to connect farmer practices with pest-management information (Matowo et al. 2022). For sugarcane production, extension activities could link weather observations with practical scouting procedures, varietal information, ratoon management, and appropriate crop-protection decisions.

The policy relevance of the study thus rests on strengthening the evidence base for plantation-level surveillance. The findings provide a basis for integrating local weather observations with YSA monitoring and with routine records of variety, ratoon status, white scale, and smut. Further validation across Tanzanian sugarcane environments would be required before these relationships are incorporated into formal pest-warning systems or operational climatic thresholds.

5. Conclusion

Sustainable pest and disease management in the Kilombero sugarcane plantation requires a management framework that considers climatic variability together with crop history, varietal characteristics and temporal patterns of infestation. The study establishes that YSA occurrence was more closely associated with temperature variation than rainfall, while white scale and smut displayed distinct patterns across varieties, ratoon systems and observation periods. These relationships provide a basis for strengthening plantation surveillance without treating climatic variables as universal predictors of pest or disease occurrence.

The findings support a shift from uniform pest and disease management towards field surveillance that combines local weather observations, regular scouting, variety records and ratoon history. Such an approach could improve the timing of management interventions while reducing reliance on routine responses that are not linked to observed pest and disease conditions. The absence of organism-specific climate models for white scale and smut also defines an important boundary of the present evidence. Future monitoring should maintain separate climate–organism assessments for these pests and diseases before operational thresholds are developed.

Within the study setting, climate-informed surveillance, integrated pest and disease management, appropriate varietal deployment and systematic ratoon monitoring provide a practical framework for sustaining sugarcane production. The approach links crop protection with efficient resource use and climate-responsive decision-making, supporting the food security and environmental sustainability dimensions of sugarcane production in Tanzania.

Declarations

Author Contribution

B.H.M. Conceptualization, Writing – original draft, Writing – review & editing, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. P.M.N. Supervision, Writing – original draft, Writing – review & editing, Validation. C.O.J. Supervision, Writing – original draft, Writing – review & editing, Visualization, Validation.

Data Availability

All data supporting the findings of this study are available within the paper.

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Figures

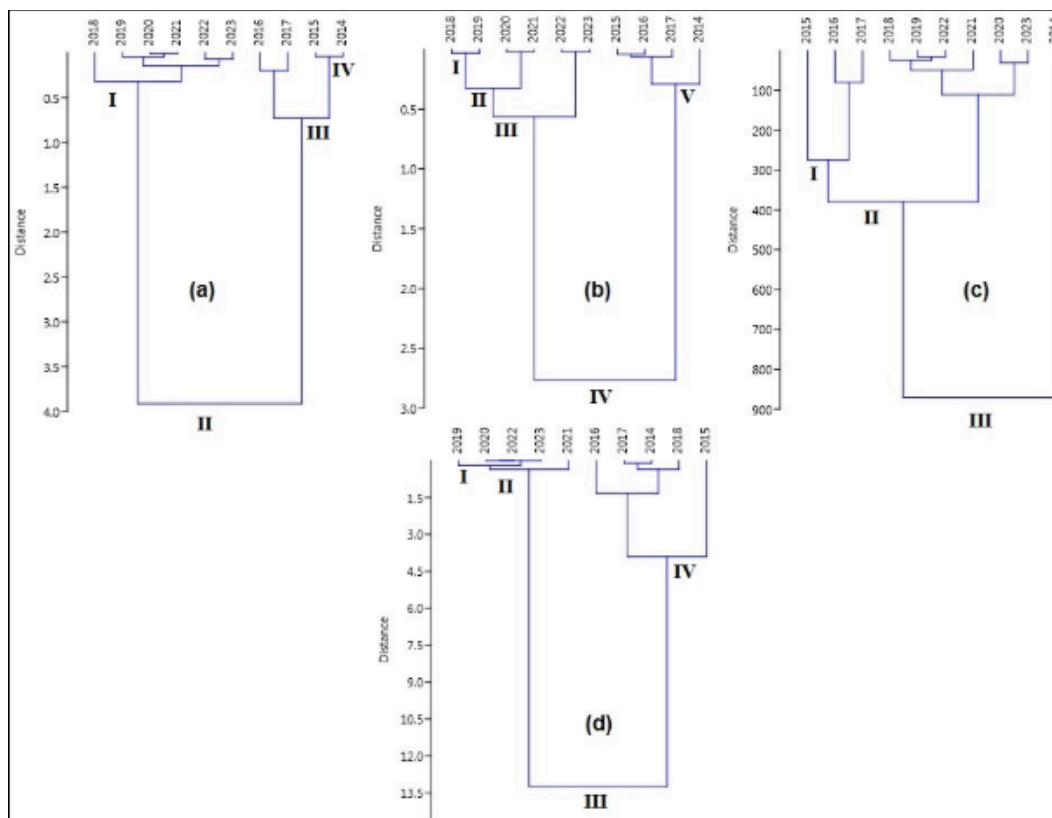


Figure 1

Cluster analysis of annual YSA infestation and climatic variables at Kilombero Sugarcane Plantation, 2014–2023.