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Influence of climatic factors on the spatial and temporal distribution of mealybugs, vectors of swollen shoot disease of cocoa tree in Koda, South-West Côte d'Ivoire

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ABSTRACT

Mealybugs are known vectors of Cocoa Swollen Shoot Virus (CSSV). Understanding the interactions between these insects and climatic factors is essential for the development of effective control strategies. The objective of this study is to determine the spatio-temporal distribution of mealybugs in relation to climatic variables. Mealybug populations were monitored within a one-hectare (1 ha) experimental plot, subdivided into five (5) quadrats measuring 20 m × 20 m each. Observations were conducted on the number of mealybugs present on each tree within the different quadrats. Climatic data, including relative humidity and temperature, were recorded monthly over a two-year period, from January 2018 to December 2019. Rainfall and wind speed data were obtained from the weather station of the International Centre for Research in Agroforestry. Throughout the two-year study period, mealybugs were present year-round. The highest population densities were observed in January and April, with a peak in April. Statistical analysis revealed significant correlations between mealybug populations and temperature (r = 0.37), relative humidity (r = −0.50), and wind speed (r = 0.47), all with $p < 0.05$. No significant correlation was found between rainfall and mealybug fluctuations (r = −0.06; $p = 0.66$). Spatial analysis indicated heterogeneous distribution of mealybugs across the different plots. These findings provide a solid scientific foundation for the development of predictive models and the implementation of targeted, sustainable integrated pest management strategies to the agroclimatic conditions of Côte d'Ivoire.

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INTRODUCTION

Mealybugs (Hemiptera; Pseudococcidae) constitute a significant group of phytophagous insects, widely recognised as crop pests (Daane *et al.*, 2012; Kondo and Watson, 2022). They infest a wide range of plants, including ornamental species, vegetable crops, fruit trees, and notably, the cacao tree (*Theobroma cacao* L.) (Aidoo *et al.*, 2022). The damage they cause is both direct and indirect. Direct damage results from their sap-sucking feeding behaviour, leading to foliar chlorosis, stunted growth, fruit deformation, and gradual plant decline (N'guettia *et al.*, 2017; Tayyab *et al.*, 2024). Indirect damage is associated with the excretion of honeydew, which is rich in sugars and promotes the development of sooty moulds. These moulds cover leaves and fruits, reducing photosynthesis and the commercial quality of produce (Sultana *et al.*, 2021).

Moreover, several mealybug species act as vectors of viruses, notably badnaviruses responsible for Cacao Swollen Shoot Virus disease (CSSV) (Ramos-Sabrinho *et al.*, 2021). Endemic to West Africa, CSSV manifests through leaf reddening, vein clearing, swelling of stems and roots, followed by defoliation, branch desiccation, and progressive canopy destruction, resulting in significant yield losses (Oro *et al.*, 2020; Domfeh *et al.*, 2023). First identified in Ghana in 1936, where it devastated thousands of hectares of cacao plantations, CSSV remains a major constraint to cacao production, including in Côte d'Ivoire, the world's leading producer (N'guettia *et al.*, 2021; Abrokwah *et al.*, 2022).

The mealybugs that transmit this disease are soft-bodied oviparous insects, whose life cycle comprises three larval stages. This cycle is strongly influenced by environmental conditions. Temperature and humidity affect their development rate, survival, and fecundity (Peng *et al.*, 2025; El Aalaoui and Sbaghi, 2022). Generally, population dynamics and dispersal are modulated by abiotic factors. Recent studies show that extreme temperatures condition their activity: optimal development occurs between 20 and 30 °C, while temperatures above 33–35 °C lead to increased mortality (Waters, 2021; Aidoo *et al.*, 2022). High relative humidity may favour their development, but heavy rainfall acts as a mortality factor, particularly during the dispersal phase (Aidoo *et al.*, 2022). Passive dispersal of first-instar larvae by wind also facilitates the colonisation of new hosts and new areas (Estay *et al.*, 2023; Hodges *et al.*, 2024). In this context, a key question arises: do the observed climatic changes in Côte d'Ivoire influence the population dynamics of cacao mealybugs? Despite the economic importance of cacao for Côte d'Ivoire and the threat posed by CSSV, data on the population dynamics of vector mealybugs remain scarce. This lack of fundamental ecological knowledge limits the development of predictive models and effective integrated pest management strategies. To bridge this gap, we conducted a study on the spatio-temporal distribution of mealybugs in the cocoa plantations of Koda (Soubré), in relation to climatic factors.

MATERIALS AND METHODS

Study area

The study was conducted in Koda (6°38′W, 5°56′N), a village located in the Soubré Department, capital of the Nawa Region, in south-western Côte d'Ivoire. The research took place over a two-year period, from January 2018 to December 2019, in smallholder cocoa plantations aged between 15 and 50 years. Soubré is situated in a forested zone where the vegetation is predominantly dense tropical forest. The area is characterised by deep, permeable, and well-drained soils, which are highly suitable for various crops, particularly cocoa. This region was selected not only because it is the country's principal cocoa-producing area, but also due to the threat posed by Swollen Shoot Disease. The climate is equatorial, with high annual rainfall ranging from 1,400 mm to 1,600 mm. Consequently, the region experiences very high atmospheric humidity (around 90%) and a low annual thermal amplitude (approximately 3°C). The area is marked by two rainy seasons and two dry seasons in alternation. The first rainy season extends from March to mid-June, peaking in June, followed by a short dry season in July. Rainfall increases again and continues until the end of October, with a peak in

September, followed by the long dry season from November to the end of February.

Experimental setup

The experimental set-up comprised a single one-hectare (1 ha) block, subdivided into five quadrats measuring 20 m × 20 m each, with one quadrat positioned at each corner and one at the centre of the block (Minengu *et al.*, 2018; N'guettia *et al.*, 2021). Within each quadrat, 26 trees were randomly selected and numbered. This arrangement was replicated across three separate one-hectare plots.

Observation and data collection

Observations were carried out on the number of mealybugs present on cacao trees, alongside the collection of climatic data. Mealybugs were counted on various cacao tree organs, including pods, cherelles (young pods), flowers, and the trunk, at heights ranging from zero (0) to two (2) metres. In-situ counts were conducted for up to 100 individuals. When populations exceeded this number, insects were collected using flexible forceps and placed into pillboxes containing 70% ethanol. Each pillbox was labelled with the site name, plot number, block number, tree number, and date of observation. Samples were then transported to the laboratory for enumeration. Infested organs were marked with adhesive tape to allow the monitoring of the same infestation foci. Counts were carried out twice monthly (on the 1st and 15th) throughout the 2018–2019 period, in parallel with climatic measurements.

The climatic variables considered in this study included temperature, relative humidity, rainfall, and wind speed. Mean temperature and mean relative humidity were recorded using EL-USB 2 data loggers permanently installed in each plot. Rainfall and wind speed data were obtained from the weather station of the International Centre for Research in Agroforestry (ICRAF), located approximately 10 km from the study plots.

Data analysis

The data collected on mealybug population monitoring was entered and organised by observation date using Microsoft Excel 2016. The aim was to calculate the average number of mealybugs per tree over time. Additionally, mean values for temperature, relative humidity, rainfall, and wind speed were computed. The average number of mealybugs was used to illustrate population trends in relation to the mean values of the various climatic factors at the study site. One-way analyses of variance (ANOVA) were performed to compare the means obtained. Pearson correlation analysis was applied to assess the relationship between temperature, relative humidity, rainfall, wind speed, and mealybug abundance over the study period. All statistical analyses were conducted using Statistica version 7.1.

RESULTS

Spatial and temporal dynamics of mealybug abundance in Koda

The study of population dynamics in 2018 and 2019 revealed that mealybug abundance varied across the different plots. In Plot 1, the number of mealybugs collected represented 48.15% or 40.77% of the total insects recorded in the locality (Fig. 1a). In Plot 2, abundance was 51.44%, corresponding to 43.56% of the population (Fig. 1b). In Plot 3, the abundance was 18.49%, or 15.67% of the sampled insects (Fig. 1c). A one-way analysis of variance (ANOVA) revealed a statistically significant effect of plot on mealybug abundance over the two years of observation ($F = 11.89$; $p < 0.05$), confirming that population levels differed markedly among the sampled sites.

Climatic conditions during the experiment

Analysis of the climatic data indicated that the months of February, March, April, May, October, and November were the warmest, with temperatures ranging between 29°C and 31°C. The remaining months recorded temperatures between 27°C and 28°C during the two-year observation period (Table 1). The overall mean temperature was 28.75°C ± 0.77 in 2018 and 29.30°C ± 1.42 in 2019. One-way analysis of variance (ANOVA) revealed no statistically significant difference in temperature between the two years ($F = 2.70$; $p = 0.10$).

Table 1. Mean values of climatic data over the two years of observation

Month	2018				2019			
	Temp. °C	Humidity (%)	Rainfall (mm)	Wind (m/s)	Temp. °C	Humidity (%)	Rainfall (mm)	Wind (m/s)
January	29.11	64	3.3	4.09	29.71	65.29	16	4.02
February	30.21	64.96	78.99	5.02	30.29	64.98	26.92	4.32
March	29.11	67.95	149.6	5.11	30.78	62.61	34.29	4.79
April	29.4	70.25	123.7	5.22	30.17	69.35	239.76	5.12
May	29.33	70.23	97.78	4.86	29.93	71	193.29	4.31
June	27.87	74.46	141.47	3.87	28.29	74.45	154.93	3.05
July	27.78	72.71	106.7	4.07	27.4	75.44	71.62	3.39
August	27.55	72.18	217.93	4.45	27.17	75.94	111.25	3.36
September	28.38	73.2	175.76	4.12	28.59	74.49	179.58	3.82
October	29.01	71.16	205.73	4.11	28.53	75.18	142.24	4.14
November	29.14	71.22	79.5	4	31.98	87.14	119.63	4.1
December	28.22	69.53	18.79	3.36	28.37	72.48	99.31	3.49

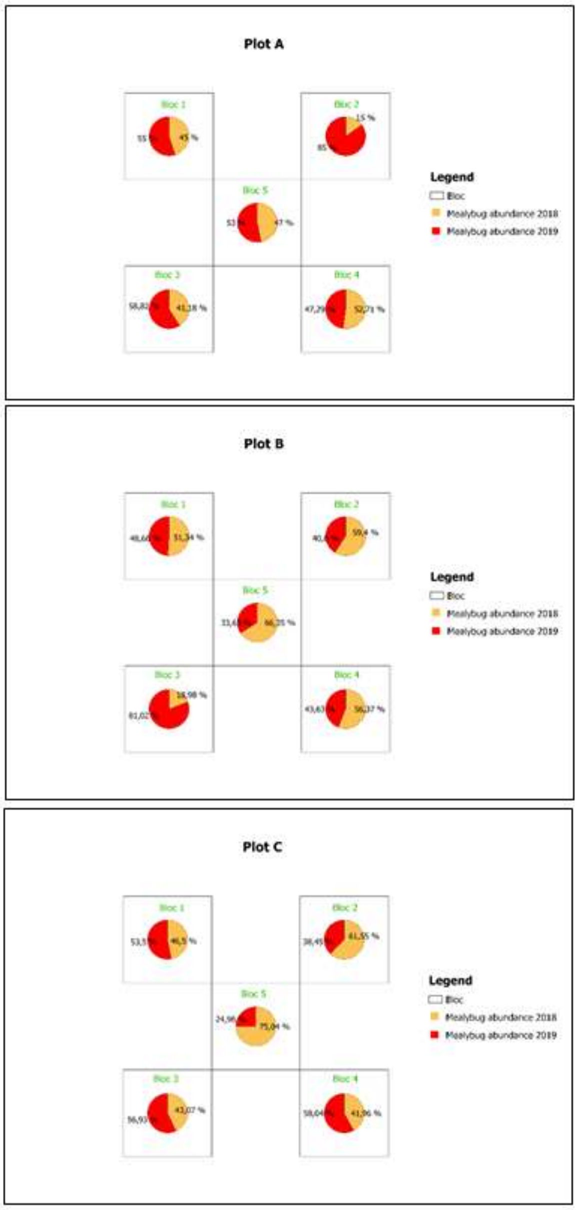

Fig. 1. Spatial distribution map of mealybug abundance

Relative humidity during the 2018–2019 period ranged significantly between 74% and 87% during the months of June, July, August, September, October, and November (Table 1).

The overall mean relative humidity was recorded at 70.15% ± 3.10 in 2018 and 72.35% ± 6.52 in 2019. However, ANOVA analysis did not reveal a statistically significant difference in humidity between the two years ($F = 2.21$; $p = 0.14$).

Rainfall varied both monthly and annually. In 2018, the highest rainfall was recorded in August (217.93 mm) and October (205.73 mm). In contrast, in 2019, peak rainfall occurred in April (239.76 mm) and May (195.29 mm). Drier conditions were observed in January (3.3 mm) and December (18.79 mm) in 2018, and in January (16 mm), February (26.92 mm), and March (34.29 mm) in 2019. The overall mean rainfall was 116.60 mm ± 65.35 in 2018 and 116.44 mm ± 70.25 in 2019 (Table 1). ANOVA revealed no significant difference in rainfall between the two years ($F= 0.0001$; $p= 0.99$).

Wind speed increased from January to April, with average speeds ranging between 4 m/s and 5 m/s during both years of observation (Table 1). The mean wind speed was 4.35 m/s ± 0.57 in 2018 and 3.99 m/s ± 0.60 in 2019. ANOVA revealed a statistically significant difference in wind speed between the two years ($F= 4.39$; $p= 0.04$).

Influence of temperature on mealybug abundance

Analysis of Fig. 2 indicates that, across both years, April consistently recorded the highest mealybug populations, with 20–22 individuals per tree, at an average temperature of 29.4°C. Additionally, moderate population levels were observed in January, with average abundances of 10.34 individuals per tree in 2018 and 9.51 in 2019, when temperatures ranged between 29.11°C and 29.71°C.

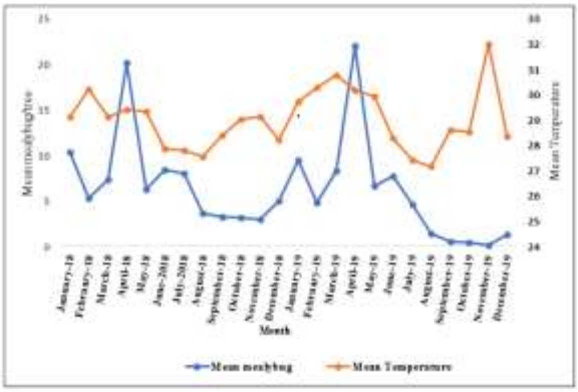

Fig. 2. Monthly fluctuation of mealybugs in relation to mean temperature

The lowest populations, ranging from 2 to 4 individuals per tree, were recorded between May and December in both years, corresponding to temperatures between 29.63°C and 28.29°C. Pearson's correlation test revealed a significant positive relationship between mealybug abundance and temperature (r = 0.37, $p < 0.05$) (Fig. 3).

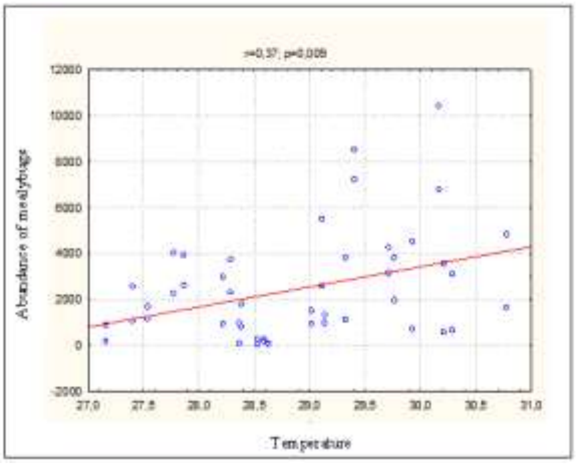

Fig. 3. Correlation between mealybug abundance and temperature

Influence of humidity on mealybugs

Analysis of Fig. 4 shows that in both 2018 and 2019, April recorded the highest mealybug populations (20-22 individuals per tree), under relative humidity levels of 70.25% and 69.35%, respectively. Additionally, moderate populations (9-10 individuals per tree) were observed in January, with an average of 10.34 mealybugs per tree in 2018 at 64% humidity, and 9.51 in 2019 at 65.29% humidity.

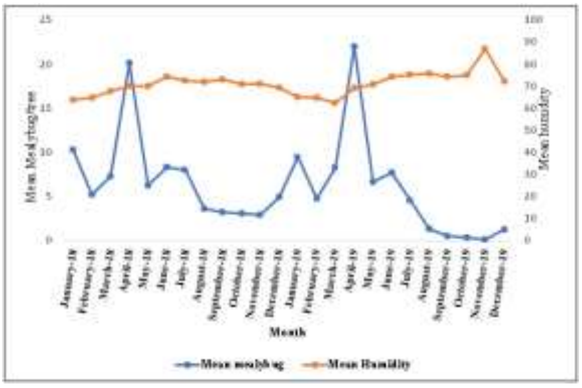

Fig. 4. Monthly fluctuation of mealybugs in relation to mean humidity

The lowest populations (2-4 individuals per tree) were recorded between May and December in both years, under relative humidity levels ranging from 70.61% to 71%. Pearson's correlation test revealed a significant negative relationship between mealybug abundance and relative humidity (r = −0.50, $p < 0.05$) (Fig. 5).

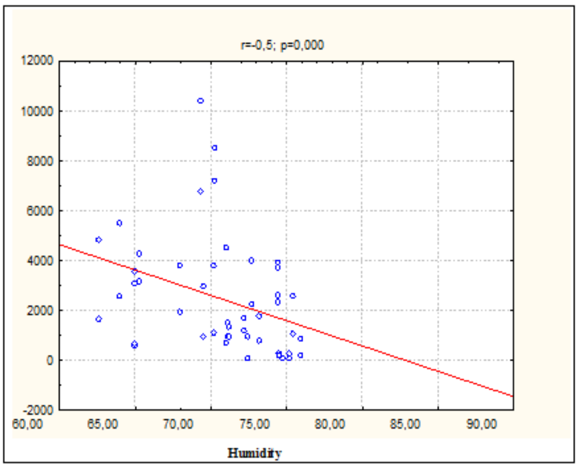

Fig. 5. Correlation between mealybug abundance and relative humidity

Influence of wind strength on mealybug fluctuation

Statistical analyses revealed a significant positive influence of wind speed on mealybug population trends ($r = 0.47$; $p < 0.05$) (Figs 6 and 7). Regardless of the year, April recorded the highest mealybug populations, coinciding with elevated wind speeds 5.22 m/s in 2018 and 5.12 m/s in 2019. Below these wind speeds, population levels declined.

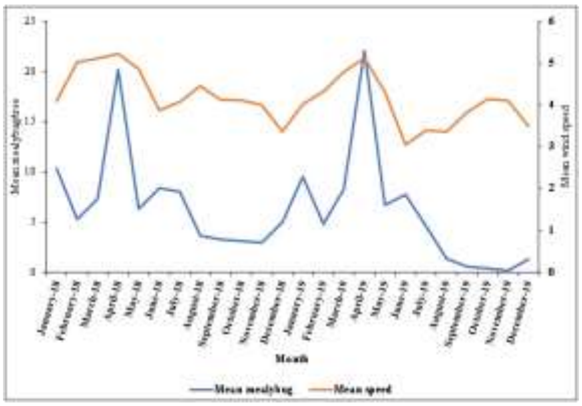

Fig. 6. Monthly fluctuation of mealybugs as a function of wind speed

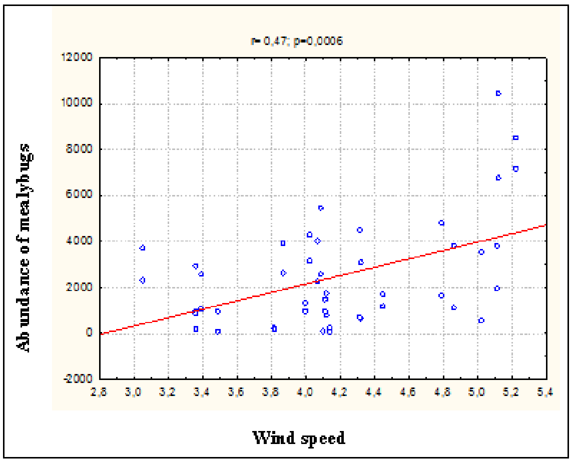

Fig. 7. Correlation between mealybug abundance and wind speed

Moderate populations (9-10 individuals per tree) were observed in January, with averages of 10.34 mealybugs per tree in 2018 and 9.51 in 2019, under wind speeds of approximately 4 m/s. The lowest populations were recorded between May and December, when wind speeds ranged between 3 m/s and 4 m/s.

Influence of rainfall on mealybug fluctuation

Overall, it was observed that high mealybug abundances tended to occur during periods of low rainfall, and vice versa, with the exception of April 2019 (Fig. 8). An average abundance of approximately 10 scale insects per tree was recorded in January 2018 and 2019, under low rainfall conditions of 3.3 mm and 16 mm, respectively.

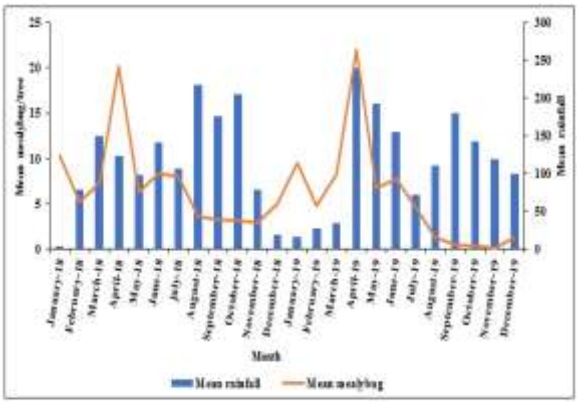

Fig. 8. Monthly fluctuation of mealybugs in relation to rainfall

Regardless of the year of study, April consistently recorded the highest mealybug populations per tree. In 2018, a high abundance of 20.16 individuals per tree coincided with 123.7 mm of rainfall. In contrast, in 2019, the highest mealybug abundance (22.04 individuals per tree) occurred alongside the highest rainfall value (239.76 mm).

The lowest populations were recorded between May and December in both years, when rainfall ranged from 97.78 mm to 217.93 mm. However, Pearson's correlation test revealed no statistically significant relationship between mealybug abundance and rainfall ($r = -0.06$; $p = 0.66$).

DISCUSSION

Mealybugs are present in cacao orchards throughout the year, with high population densities observed in January and April. This result may be linked to the availability of food resources, which are essential for mealybug survival. Indeed, the persistence of flowers, cherelles (young pods), and mature pods favourable for mealybug feeding was noted during the study period. According to Lahive *et al.* (2018) and Suarez *et al.* (2025), climatic conditions influence cacao tree physiology by affecting the growth of new leaves, flowering, and fruiting. This physiological process is triggered at the onset of the rainy season, which extends from April to July, in anticipation of a good harvest from September to January. Given the intermediate harvest, a second flowering period occurs from November to January (Perez-Flores *et al.*, 2025). Flowering peaks coincide with the dry season (January to March) and the beginning of the rainy season (mid-March to April). These findings are consistent with those of Borkakati *et al.* (2024), who observed a similar seasonal pattern in mealybug populations on mango trees.

The study revealed a heterogeneous distribution of mealybugs across the different plots. This result may be explained by differences in plot maintenance, climatic variability between plots, and physical factors specific to each plot.

These findings support those of Borkakati *et al.* (2024), who reported variations in mango mealybug incidence between plots, attributed to microclimatic conditions within the orchard. According to Poornakala *et al.* (2025), shading and food availability within each plot promote mealybug proliferation, whereas high sunlight exposure reduces their numbers in the orchard.

Regarding the influence of average temperature on mealybug populations, a significant positive correlation was observed. These results suggest that temperature plays a decisive role in the demographic parameters of mealybugs. Temperature significantly affects insect development rates. Nitya Sree *et al.* (2023) reported that temperature substantially shortens the sexual maturation period of mealybugs, which facilitates their multiplication.

Similarly, several authors have noted that mealybug growth rates are directly proportional to temperature increases (Bhau and Abrol, 2023; Harbi *et al.*, 2025). Bhau and Abrol (2023) demonstrated that the development of *Drosicha mangiferae* was positively influenced by temperature. Peak mealybug populations were recorded at temperatures between 29°C and 30°C. This trend aligns with the observations of Tanga *et al.* (2019) and Nitya Sree *et al.* (2023), who showed that temperature induces the most pronounced changes in *Phenacoccus manihoti* between 27°C and 30°C. Analysis of the influence of humidity on mealybug abundance revealed that high relative humidity values lead to a decrease in population size. Nitya Sree *et al.* (2023) and Hazarika and Dutta (2020) indicated that elevated relative humidity results in reduced mealybug populations.

Temperature and relative humidity generally have opposing functions in nature, and these two parameters may exert contrasting effects on the mealybug developmental cycle in orchards. According to Kumawat and Sharma (2024), a decrease in relative humidity leads to an increase in temperature. Thus, unlike temperature, high relative humidity prolongs the mealybug developmental cycle, resulting in reduced population sizes.

These authors highlighted the role of relative humidity in the development of cassava mealybugs. It was established that increased relative humidity tends to extend the developmental duration of mealybugs but also increases mortality at extreme values. Low population densities were observed during the major rainy season.

This result may be explained by the mechanical action of rainfall, which causes the washing away of mealybugs observed across the study plots. Similar findings were reported by Tanga *et al.* (2019). Hazarika and Dutta (2020) also found that rainfall significantly reduced populations of *Paracoccus marginatus* on papaya and mulberry.

Furthermore, Georgopoulou *et al.* (2024) observed a negative correlation between rainfall and populations of *Maconellicoccus hirsutus*. Analysis of the influence of wind speed showed that higher values led to increased mealybug populations.

This may be due to the mechanical action of wind, which facilitates mealybug dispersal. This mechanism could alter mealybug abundance from one plot to another. High mealybug populations were observed at wind speeds between 4 m/s and 5 m/s, while minimum populations were recorded between 3 m/s and 4 m/s. Borkakati *et al.* (2024) also reported that wind speed negatively affected mealybug populations, suggesting that dispersal mechanisms vary depending on species and host plants.

CONCLUSION

This study highlighted the continuous presence of mealybugs in cacao plots throughout the year, with population levels varying according to the seasons. A consistently high abundance was recorded in April across multiple years, while lower densities were observed between May and December. The results demonstrated that certain climatic factors, particularly average temperature and wind speed, exert a significant and positive influence on mealybug population fluctuations. In contrast, relative humidity and rainfall showed a significant negative correlation, indicating their limiting role in the development of these insects.

These observations contribute to a better understanding of the ecological dynamics of mealybugs in cacao orchards and provide a robust scientific foundation for the development of targeted control strategies. In particular, they pave the way for integrated management approaches aimed at reducing populations of mealybugs that act as vectors of Swollen Shoot disease, thereby contributing to the sustainable protection of cacao plantations.

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