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Climate and Soil Factors in the Control of Swollen Shoot Disease

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Abstract

Swollen shoot is a viral disease of the cocoa tree in the major cocoa-producing areas of West Africa. Its progression can be influenced by several factors, including climate and soil. This study aims to assess the impact of mealybug vectors, climate and soil on the spread of swollen shoot disease in order to develop more effective control methods. It was done in the counties of Abengourou, Bouaflé, Divo and Soubré. Three plots showing early signs of infection were selected in each department. Thus, 6 concentric lines from a disease foci in different directions were defined and each line includes 9 unaffected cocoa trees. These cocoa trees were tracked for 2 years. The data collection consisted of determining the number of diseased and dead trees as well as the number of colonies of mealybug species on each tagged cocoa plant. In addition, composite samples were taken in the 0–60 cm stratum of each plot to determine the texture, composition of organic matter and soil chemicals. Then, climate data, including rainfall and temperature, were collected over the observation period. The variance analysis indicated homogeneity between the dry and wet seasons, between clay-silt and clay-sandy soils, and between soils low in organic matter and those with acceptable organic matter, in terms of disease effects and mealybug populations. However, in the dry season, the Pearson correlation was significant between these variables in the departments. Thus, it was also significant between the level of sand, potassium (K^{+}), magnesium (Mg^{2+}), and exchangeable phosphorus contents, and the pH according to the textures studied and the soils poor in organic matter. Water deficit, texture, organic matter and nutrients of the cocoa tree are the factors that impact the spread of swollen shoot disease. These factors can therefore be used to implement an effective measure to combat swollen shoot disease.

Keywords: Cocoa, Swollen shoot, season, soil, Mealybugs

Introduction

Côte d'Ivoire, the world's largest cocoa producer since the 1977-1978 season, has been under severe pressure from swollen shoot disease since its resurgence in 2003 in the orchard (Kébé et N'guessan, 2003). Indeed, the swollen shoot was first described in 1943 in the eastern cocoa-producing areas of Côte d'Ivoire. However, the damage of the disease was significant only from 2003 when it reappeared in the Ivorian orchard.

Swollen shoot disease, also known as cocoa twig swelling disease, remains a major challenge for cocoa farming. This disease, transmitted by several species of mealybugs, can potentially reduce yield by about 30% to 50% and even cause the death of cocoa trees within 2 to 3 years after infection (Muller, 2016). Although it was first identified in Ghana (Steven *et al.* 1936), the disease is now widespread in all major cocoa-producing countries in West Africa.

The swollen shoot is now considered a formidable threat to cocoa crops in Côte d'Ivoire, where it contributes significantly to the decline in production and the mortality of affected trees (Kouakou, 2014). According to Aka *et al.* (2020), from 2008 to 2016, the prevalence of swollen shoot disease was estimated at 19.51% with 19 out of 24 infected regions encompassing 83 departments and 40,680 farms. To date, the disease has led to the disappearance of several cocoa plots in the major production zone of Côte d'Ivoire. This reflects the strong pressure of this disease on Ivorian cocoa farming. In addition, one of the consequences of this disease is that Ivorian cocoa production, which reached 2 million tons since the 2016-2017 season (ICCO, 2019), is now 1.6 million tons during the 2023-2024 season (ICCO, 2025).

Several biotic and abiotic factors help explain the spread of swollen shoot disease in the orchard. However, the interactions between these factors and disease are not well defined. Thus, the study of the dynamics of vectors, in particular mealybugs, the effect of soil nutrition and climatic parameters on the epidemiology of the disease is necessary (Ameyaw *et al*., 2023).

The purpose of this study is to determine the impact of scale vectors, climate and soil on the spread of swollen shoot disease to develop more effective control techniques.

Materials and methods

Materials

Study site

The study was done in the counties of Abengourou, Bouaflé, Divo and Soubré. The county of Abengourou is in the east of Côte d'Ivoire between latitudes 5°45 and 7°10 North and longitudes 3°10 and 3°50 West (Aka *et al.*, 2013). It belongs to the domain of the dense humid forest. The climate is sub-equatorial, hot and humid with an average temperature of 26 C. Precipitation is estimated to average 1,200 mm of rain per year (Aka, 2010). It is the former flagship area of cocoa cultivation and is now distinguished by aging plantations. It was also in this region, more precisely in Sankadiokro (county of Abengourou) and Kongodia (county of Agnibilékrou), that the swollen shoot disease was detected for the first time in Côte d'Ivoire (Alibert, 1946).

The county of Bouaflé is located in the central-western part of Côte d'Ivoire between longitudes 5°45 and 5°47 west and latitudes 6°57 and 7°00 north. It lies between the mesophilic and ombrophillic climate zones of the Guinean domain (Diomandé *et al*., 2014). The average annual rainfall fluctuates around 1150 mm, with a temperature that varies from 25.2 to 26.5°C per year. The department of Bouaflé is an essentially agricultural region with good cocoa production. However, the resurgence of swollen shoot disease in 2003 led to considerable losses in cocoa production in this region (Kébé & N'Guessan, 2003).

The county of Divo (5°50'29.54 N and 5°21'45.19 W) is located in the South-West region of Côte d'Ivoire. It is subject to a humid sub-equatorial climate with an average annual rainfall of 1,400 mm and an average temperature of 26 °C. This area is also marked by the ageing of cocoa orchards and the decrease in soil fertility (Aka *et al*., 2013; Yao *et al*., 2014). According to Koua *et al.* (2018), the Swollen Shoot disease is becoming a concern for cocoa farmers in the department of Divo.

The county of Soubré is located on the south-western side of Côte d'Ivoire between latitudes 5°19 and 6°34 N and longitudes 6°12 and 7°08 W. This region records annual rainfall of between 1,600 mm and 1,800 mm with temperatures between 26°C to 32°C during the year (Yao *et al*., 2014). During the 1970s and 1980s, cocoa farming experienced remarkable growth, expanding into new pioneer areas, forming what is known as the "New Cocoa Loop" (Aka *et al*., 2013). However, this region faces two serious threats: swollen shoot disease and brown pod rot, two major cocoa diseases.

Plant material

The plant material came from farmers' cocoa trees in the counties of Abengourou, Bouaflé, Divo and Soubré.

Animal material

The animal material consisted of classified mealybug species in this study into two groups according to their frequency of observation described by several authors including N'Guessan (2021) and N'Guettia *et al*., (2022). Thus, group 1, the most abundant, was composed of the species *Formicococcus njalensis*, *Planococcus citri* and *Ferrisia virgata* and group 2 was composed of the species *Pseudococcus longispinus*, *Phenacoccus hargreavesi*, *Dysmicoccus brevipes* and *Planococcus kenyae*.

Methods

Experimental design

The impact of climate on the spread of swollen shoot disease and the dynamics of mealybug species was studied using a Fisher block approach across seasons in each department. Two seasons (dry and wet) were studied four times, following quarters of two consecutive years.

The study of soil interaction in the spread of swollen shoot disease and in the dynamics of mealybug species was a survey in which questionnaires focused on soil texture and organic matter content.

Preparation of the study

Three (03) plots were chosen based on accessibility and the characteristic presence of symptoms of swollen shoot disease in four departments. In each plot, a nascent outbreak was identified and monitored for two (02) years to study the progression of the disease. In addition, six (06) concentric lines of unaffected cocoa trees extending from the site in various directions around it were identified. On each line, 9 cocoa trees were tagged and monitored for two years. The choice of the number of plots, lines and cocoa trees was intended to cover the counties and plots respectively and to ensure statistical robustness.

Data Collection

The collected data focused on the dynamics of the disease and mealybug species, rainfall and temperature, and soil parameters. Disease dynamics data were collected quarterly, while mealybug data were collected monthly. They consisted of determining the presence of symptoms of the disease and counting the number of mealybug colonies on each marked cocoa plant. Affected and dead cocoa plants, and the number of mealybug colonies were reported. Healthy cocoa trees had a score of 0 and sick or dead ones had a score of 1.

At ground level, composite samples were collected from the 0–60 cm stratum of each plot. These samples were analysed in the laboratory. These analyses focused on the texture and composition of soil organic matter. Thus, the soils were studied according to the content of sand, clay and silt and their level of organic matter.

Rainfall and temperature data for each department were provided by the specialised unit in climatological studies of the National Center for Agronomic Research (CNRA). These data allow to obtain a breakdown of the dry and wet seasons of each city. These seasons were divided into quarters according to the annual values of favorable rainfall for the cocoa tree. For Brou *et al*. (2003), a quarter is considered dry for cocoa cultivation when the rainfall of cocoa is less than 300 mm of water. Similarly, above 300 mm of water, the trimester is considered to be wet. Thus, over the two years of study, quarters 1, 4, 5 and 8 were dry. On the other hand, quarters 2, 3, 6 and 7 were wet.

Data analysis

The data collected was processed by Microsoft Excel 2016. These data were then analysed using variance analysis to assess the significance between seasons, soil types, and organic matter levels for the number of colonies of mealybug species and the effects of disease. Means were separated using the Student-Newman-Keuls test at the 5% threshold. Pearson correlations have been determined between these parameters. All these analyses were performed using SAS 9.4 software.

Results

Relationship between mealybug species and the effects of swollen shoot disease based on the climate in the county of Abengourou

The variance analysis variance analysis revealed no significant differences between the dry and wet seasons for the number of colonies of Group 1 mealybug species (P = 0.55) (*F. njalensis*, *P. citri* and *F. virgata*), the number of colonies of Group 2 scale species (P. = 0.13) (*P. longispinus*, *P. hargreavesi*, *D. brevipes* and *P. kenyae*), the number of affected (P = 0.61) and dead (P = 0.08) cocoa trees in the county of Abengourou (Table 1). In addition, in the dry season, the Pearson correlation was significant and positive between group 1 mealybug species and the number of affected (r=0.66; P=0.01) and dead (r=0.61; P=0.03) cocoa trees. In the same dry season, the number of dead cocoa trees was significantly and positively related to the number of group 2 mealybug species (r=0.74; P=0.005) and the number of affected cocoa trees (r=0.75; P=0.004) (Table 2). On the other hand, in the wet season, no link was found between the variables studied (P>0.05) (Table 3).

Table 1: Comparison of dry and wet periods for the number of mealybug colonies and the number of affected and dead cocoa trees in the county of Abengourou

Seasons	Group 1 of mealybug species	Group 2 of mealybug species	Number of cocoa trees affected	Number of dead cocoa trees
Wet	37,83 ± 4,42a	1,50 ± 0,48a	3,58 ± 1,69a	0,00 ± 0,00a
Dry	44,00 ± 6,78a	0,58 ± 0,41a	5,50 ± 2,35a	0,33 ± 0,18a
P	0,55	0,13	0,61	0,08
Mean	40,91	1,04	4,54	0,09
CV	24,32	50,58	79,68	27,04

Means with the same letter in the same column are not significantly different at the 5% threshold.

Table 2: Correlation between dry period variables in the county of Abengourou

	Group 1 of mealybug species	Group 2 of mealybug species	Number of cocoa trees affected	Number of dead cocoa trees
Group 1 of mealybug species	1			
Group 2 of mealybug species	0,50	1		
Number of cocoa trees affected	**0,66***	0,37	1	
Number of dead cocoa trees	**0,61***	**0,74***	**0,75***	1

*Significant correlation at ¨P=0,05

Table 3: Correlation between variables in the wet period in the county of Abengourou

	Group 1 of mealybug species	Group 2 of mealybug species	Number of cocoa trees affected	Number of dead cocoa trees
Group 1 of mealybug species	1			
Group 2 of mealybug species	0,45	1		
Number of cocoa trees affected	0,42	-0,004	1	
Number of dead cocoa trees	x	x	x	1

X : correlation not calculated due to zero values for the number of dead cocoa trees

Relationship between mealybug species and the effects of swollen shoot disease based on the climate in the county of Bouaflé

The variance analysis showed a significant difference between the wet and dry seasons for the number of colonies of Group 1 mealybug species (P=0.005) (*F. njalensis*, *P. citri* and *F. virgata*) and the colony number of Group 2 mealybug species (P=0.04) (*P. longispinus*, *P. hargreavesi*, *D. brevipes* and *P. kenyae*) in the county of Bouaflé. For these mealybugs, the dry season had the highest values with 54.50 colonies for group 1 and 3.91 colonies for group 2. On the other hand, the variance analysis showed no significant difference between the dry and wet seasons for the number of affected (P=0.84) and dead (P=0.32) cocoa trees (Table 4).

In the dry season, the Pearson correlation was significant and positive between group 2 mealybug species and the number of affected cocoa trees (r=0.56; P=0.05) in Bouaflé (Table 5). However, in the wet season, no link was found between the parameters assessed (P>0.05) (Table 6).

Table 4: Comparison of dry and wet periods for the number of colonies of mealybug species and the number of affected and dead cocoa trees in the county of Bouaflé

Seasons	Group 1 of mealybug species	Group 2 of mealybug species	Number of cocoa trees affected	Number of dead cocoa trees
Wet	25.16 ± 4.63B	0.08 ± 0.08B	11.83 ± 3.31a	0.00 ± 0.00A
Dry	54.50 ± 8.42a	3.91 ± 2.10a	13.16 ± 3.67a	0.16 ± 0.16a
P	0,005	0,04	0,84	0,32
Means	39,83	2,00	12,50	0,08
CV	33,82	83,07	52,87	23,99

Means with the same letter in the same column are not significantly different at the 5% threshold.

Table 5: Correlation between dry period variables in the county of Bouaflé

	Group 1 of mealybug species	Group 2 of mealybug species	Number of cocoa trees affected	Number of dead cocoa trees
Group 1 of mealybug species	1			
Group 2 of mealybug species	-0,40	1		
Number of cocoa trees affected	-0,03	**0,56***	1	
Number of dead cocoa trees	0,37	-0,17	0,34	1

* Significant correlation at 0.05

Table 6: Correlation between variables in wet periods in the county Bouaflé

	Group 1 of mealybug species	Group 2 of mealybug species	Number of cocoa trees affected	Number of dead cocoa trees
Group 1 of mealybug species	1			
Group 2 of mealybug species	-0,12	1		
Number of cocoa trees affected	-0,11	-0,19	1	
Number of dead cocoa trees	x	x	x	1

X: correlation not calculated due to zero values of the number of dead cocoa trees

Relationship between mealybug species and the effects of swollen shoot disease based on the climate in the county of Divo

In Divo County, the variance analysis variance analysis showed no significant difference between the dry and wet seasons for the number of colonies of group 1 mealybug species (P=0.42) (*F. njalensis*, *P. citri* and *F. virgata*), the number of colonies of group 2 mealybug species (P=0.31) (*P. longispinus*, *P. hargreavesi*, *D. brevipeset P. kenyae*) and the number of cocoa trees affected (P=0.96) and dead (P=0.84) (Table 7).

In the dry season, the Pearson correlation was significant and positive between the number of colonies of group 1 mealybug species and the number of dead cocoa trees (r= 0.59; P=0.04) and the number of colonies of group 2 mealybug species (r= 0.71; P=0.008). In the same season, the number of affected cocoa trees was significantly and positively related to the number of dead cocoa trees (r=0.65; P = 0.02) (Table 8).

On the other hand, in the wet season, no link was found between the parameters evaluated (P>0.05) (Table 9).

Table 7: Comparison between dry and wet periods for the number of colonies of mealybug species and the number of affected and dead cocoa trees in the county of Divo

Seasons	Group 1 of mealybug species	Group 2 of mealybug species	Number of cocoa trees affected	Number of dead cocoa trees
Wet	52.33 ± 8.41a	0.58 ± 0.26a	7,66 ± 1,77a	0.66 ± 0.22a
Dry	70.50 ± 15.42a	1.00 ± 0.32a	8.16 ± 2.08a	0.83 ± 0.34a
P	0,42	0,31	0,96	0,84
Means	61,41	0,79	7,91	0,75
CV	34,58	40,14	52,20	40,36

Means with the same letter in the same column are not significantly different at the 5% threshold.

Table 8: Correlation between dry period variables in the county of Divo

	Group 1 of mealybug species	Group 2 of mealybug species	Number of cocoa trees affected	Number of dead cocoa trees
Group 1 of mealybug species	1			
Group 2 of mealybug species	**0,71***	1		
Number of cocoa trees affected	0,45	0,41	1	
Number of dead cocoa trees	**0,59***	0,47	**0,65***	1

* Significant correlation at 0,05

Table 9: Correlation between wet period variables in the county of Divo

	Group 1 of mealybug species	Group 2 of mealybug species	Number of cocoa trees affected	Number of dead cocoa trees
Group 1 of mealybug species	1			
Group 2 of mealybug species	0,08	1		
Number of cocoa trees affected	0,47	0,17	1	
Number of dead cocoa trees	0,09	0,17	0,52	1

* Significant correlation at 0.05

Relationship between mealybug species and the effects of swollen shoot disease based on the climate in the county of Soubré

In the county of Soubré, the variance analysis revealed a significant difference between the dry and wet seasons for the number of colonies of group 1 mealybugs (P=0.02) (*F. njalensis*, *P. citri* and *F. virgata*). For this parameter, the wet season had the highest number with 32.91 colonies of mealybug species. On the other hand, the variance analysis revealed no significant difference between the dry and wet seasons for the number of colonies of group 2 mealybug species (P=0.38) and the number of affected (P=0.74) and dead (P=0.49) cocoa trees (Table 10).

In the dry season, the Pearson correlation was significant and positive between the number of affected cocoa trees and the number of dead cocoa trees (r 0.80; P = 0.04) (Table 11). In the wet season, the Pearson correlation was significant and positive between the number of colonies of group 1 scale species and the number of colonies of group 2 scale species (r= 0.60; P = 0.001) (Table 12).

Table 10: Comparison of dry and wet periods for the number of colonies of mealybug species and the number of affected and dead cocoa trees in the county of Soubré

Seasons	Group 1 of mealybug species	Group 2 of mealybug species	Number of cocoa trees affected	Number of dead cocoa trees
Wet	32.91 ± 3.17a	0.50 ± 0.33a	6,00 ± 1,53a	0.50 ± 0.15a
Dry	22.25 ± 2.87b	0.75 ± 0.25A	6.00 ± 1.89a	0.83 ± 0.34a
P	0,02	0,38	0,74	0,49
Means	27,58	0,62	6,00	0,66
CV	20,06	43,04	48,44	36,61

Means with the same letter in the same column are not significantly different at the 5% threshold

Table 11: Correlation between dry period variables in the county of Soubré

	Group 1 of mealybug species	Group 2 of mealybug species	Number of cocoa trees affected	Number of dead cocoa trees
Group 1 of mealybug species	1			
Group 2 of mealybug species	0,30	1		
Number of cocoa trees affected	0,11	0,06	1	
Number of dead cocoa trees	0,37	-0,04	**0,80***	1

* Significant correlation at 0.05

Table 12: Correlation between variables during wet periods in the county of Soubré

	Group 1 of mealybug species	Group 2 of mealybug species	Number of cocoa trees affected	Number of dead cocoa trees
Group 1 of mealybug species	1			
Group 2 of mealybug species	**0,60***	1		
Number of cocoa trees affected	-0,23	-0,17	1	
Number of dead cocoa trees	0,24	0,00	-0,22	1

* Significant correlation at 0.05

Study of soil types based on granulometry

The variance analysis revealed a significant difference between the soil types for the contents of Clay (P = 0.04) and Sand (P = 0.03). For clay content, the clay-silt soil type had the highest value with 53.49% clay, while for sand content, the clay-sandy soil type had the highest value with 31.97% sand. For silt content, the variance analysis revealed no significant differences between soil types (Table 13).

Table 13: Comparison of soil types by Clay, sand and silt content

Types of soil	Clay (%)	Sand (%)	Limon (%)
Sandy-clay	45.56 ± 2.71B	31.97 ± 3.29a	22.46 ± 0.77a
Clay-silt	53.49 ± 1.62a	21.87 ± 1.21b	24.63 ± 0.50a
P	0,04	0,03	0,06
Means	48,86	27,76	23,37
CV	12,30	25,09	7,46

Means with the same letter in the same column are not significantly different at the 5% threshold.

Study of soil types according to chemical element content

The variance analysis showed no significant differences between soil types (P>0.05) for pH, organic matter (MOS), carbon and nutrient content of the cocoa tree (Pass; K+; Ca2+ and Mg2+) (Table 14).

Table 14: Comparison of soil types by chemical content

Soil type	pH	MOS	Carbon	Pass (Cmol/kg1)	K+ (Cmol/kg1)	Ca2+ (Cmol/kg1)	Mg2+ (Cmol/kg1)
Sandy-clay	5.93 ± 0.25a	2.49 ± 0.18a	1.45 ± 0.10a	5.63 ± 0.46a	0.33 ± 0.01a	1.01 ± 0.10a	1.08 ± 0.04a
Clay-silt	6.00 ± 0.15a	2.24 ± 0.23a	1.30 ± 0.13a	6.64 ± 0.45a	0.32 ± 0.13a	1.09 ± 0.15a	1.06 ± 0.06a
P	0,83	0,41	0,41	0,16	0,77	0,64	0,83
Means	5,96	2,39	1,39	6,05	0,32	1,05	1,07
CV	9,60	20,73	20,84	18,93	10,54	28,38	11,31

Means with the same letter in the same column are not significantly different at the 5% threshold. MOS= Soil organic matter; Pass = Assimilable phosphorus.

Study of soil types according to the number of affected and dead cocoa trees and the number of colonies of mealybug species

The variance analysis revealed no significant differences (P>0.05) between soil types for the number of affected cocoa trees, the number of dead cocoa trees and the number of colonies of group 1 and 2 mealybug species (Table 15).

Table 15: Comparison of soil types according to the number of affected and dead cocoa trees and the colonies of mealybug species

Soil type	Number of affected plants	Number of dead plants	Number of Group 1 Mealybug Colonies	Number of colonies of Group 2 mealybugs
Sandy-clay	63.42 ± 17.33a	4.42 ± 1.58a	234.14 ± 42.16a	10.57 ± 5.64a
Clay-silt	49.20 ± 12.58a	1.80 ± 0.66a	293.60 ± 26.29a	6.60 ± 2.56a
P	0,63	0,34	0,25	0,61
Means	57,50	3,33	258,91	8,91
CV	33,62	51,68	19,16	57,88

Means with the same letter in the same column are not significantly different at the 5% threshold.

Relationship between the physico-chemical parameters of the soil, the number of affected and dead cocoa trees and the number of colonies of mealybug species according to the type of soil

The Pearson correlation between soil chemical element contents, the number of affected and dead cocoa trees and the number of colonies of mealybug species showed significant links between these parameters for the two soil types in this study.

For the clay-silt soil type, the correlation was significant and positive between the number of dead cocoa trees and the level of sand ($r= 0.89$ and $P=0.03$), between the organic matter content (MOS) and the carbon content ($r= 1.00$ and $p<0.0001$), magnesium ($r=0.93$ and $p=0.01$) and potassium ($r=0.92$ and $p=0.02$), between magnesium content and potassium ($r=0.99$ and $p=0.0002$) and carbon ($r=0.94$ and $p=0.01$) and between carbon and potassium ($r=0.92$ and $p=0.02$). In the same soil type, the number of dead cocoa trees and the exchangeable phosphorus content ($r= -0.95$ and $P=0.01$) and between the number of colonies of group 2 mealybug species (Coch2) and the number of cocoa trees affected ($r= -0.89$ and $P=0.04$) was significant and negative (Table 16).

For the Clay-sandy soil type, the Pearson correlation was significant and positive between the number of dead cocoa trees and the potassium ($r=0.75$ and $P=0.04$) and magnesium ($r=0.74$ and $P=0.04$) contents, between the number of colonies of group 2 mealybug species and the pH ($r= 0.77$ and $p=0.04$) and the number of cocoa trees affected ($r= 0.88$ and $p=0.008$), between calcium (Ca^{2+}) and exchangeable phosphorus content ($r=0.76$ and $p=0.04$), between organic matter and carbon content ($r=0.99$ and $p<0.0001$) and between magnesium content and potassium content ($r= 0.97$ and $p=0.0003$). In the same soil type, the Pearson correlation was significant and negative between silt and sand content (Table 17).

Table 16: Correlation between the number of affected and dead cocoa trees, the physico-chemical soil parameters and the number of mealybug colonies in the Clay-silt soil type

	Sand	Limon	pH	MOS	Pass	Ca2+	K+	Carbon	Mg2+	Ncat	Ncmort	Coch1	Coch2
Sand	1												
Limon	0,73	1											
pH	-0,50	0,08	1										
MOS	-0,23	0,32	0,53	1									
Pass	-0,83	-0,27	0,69	0,45	1								
Ca2+	-0,67	-0,04	0,75	0,85	0,83	1							
K+	-0,06	0,33	0,16	**0,92***	0,24	0,66	1						
COS	-0,23	0,32	0,53	**0,0001***	0,44	0,85	**0,92***	1					
Mg2+	-0,14	0,28	0,21	**0,93***	0,30	0,71	**0,99***	**0,93***	1				
Ncat	0,01	0,19	0,16	-0,42	0,31	-0,16	-0,53	-0,42	-0,54	1			
Ncmort	**0,89***	0,45	-0,48	-0,39	-**0,95***	-0,77	-0,27	-0,39	-0,33	-0,17	1		
Coch1	-0,30	-0,34	-0,13	-0,58	0,36	-0,20	-0,57	-0,58	-0,56	0,80	-0,41	1	
Coch2	0,28	-0,17	-0,54	0,03	-0,65	-0,29	0,24	0,03	0,22	**-0,89***	0,48	-0,65	1

* Significant correlation at 0.05. MOS= Soil organic matter; Pass= Assimilable phosphorus; Ncat= Number of cocoa trees affected; Ncmort = Number of dead cocoa trees; Coch1=Number of colonies of group 1 mealybug species; Coch2= Number of colonies of group 2 mealybug species

Table 17: Correlation between the number of affected and dead cocoa trees, the physico-chemical soil parameters and the number of mealybug colonies in the Sandy clay soil type

	Sand	Limon	pH	MOS	Pass	Ca2+	K+	Carbon	Mg2+	Ncat	Ncmort	Coch1	Coch2
Sand	1												
Limon	**-0,80***	1											
pH	0,22	0,08	1										
MOS	0,13	-0,27	-0,33	1									
Pass	-0,19	0,64	0,47	0,003	1								
Ca2+	-0,07	0,31	0,30	0,61	**0,76***	1							
K+	-0,09	-0,17	-0,09	0,72	0,11	0,56	1						
COS	0,13	-0,27	-0,34	**0,99***	0,001	0,61	0,72	1					
Mg2+	-0,03	-0,09	0,02	0,70	0,02	0,69	**0,97***	0,70	1				
Ncat	-0,21	0,27	0,65	-0,45	0,65	-0,05	-0,06	-0,46	-0,05	1			
Ncmort	0,24	0,24	-0,47	0,72	0,72	0,26	**0,75***	0,73	**0,74***	-0,33	1		
Coch1	**0,90***	-0,60	0,02	0,16	0,008	0,02	-0,06	0,16	0,06	-0,33	0,41	1	
Coch2	-0,31	0,34	**0,77***	-0,50	0,30	0,07	0,04	-0,51	0,06	**0,88***	-0,44	-0,45	1

* Significant correlation at 0.05. MOS= Soil organic matter; Pass= Assimilable phosphorus; Ncat = Number of cocoa trees affected; Ncmort = Number of dead cocoa trees; Coch1=Number of colonies of group 1 mealybug species; Coch2= Number of colonies of group 2 mealybug species

Study of soil organic matter levels based on the content of chemical elements

The variance analysis showed a significant difference between soils low in organic matter and soils with acceptable organic matter (MOS), carbon, potassium (K+) and magnesium (Mg2+) contents. For these variables, soils with acceptable organic matter had the highest values with

2.68% for the organic matter rate; 1.56% for carbon; 0.34 Cmol/kg for potassium content and 1.13 Cmol/kg for magnesium content (Table 18).

Table 18: Comparison of soil organic matter levels by chemical content

Soil type	pH	MOS (%)	Carbon (%)	Pass (Cmol/kg1)	K+ (Cmol/kg1)	Ca2+ (Cmol/kg1)	Mg2+ (Cmol/kg1)
Soils with acceptable organic matter	5,84±0,18a	2.68 ± 0.09a	1,56± 0,05a	6,05± 0,52a	0,34± 0,00a	1,15± 0,10a	1,13± 0,02a
Soils poor in organic matter	6,21± 0,28a	1,79± 0,07b	1,04± 0,04b	6,08± 0,29a	0,29± 0,01b	0,85± 0,07a	0,95± 0,05b
P	0,28	0,0001	0,0001	0,96	0,003	0,10	0,005
Means	5,96	2,39	1,39	6,06	0,32	1,05	1,07
CV	9,07	9,52	9,51	20,94	6,60	24,87	7,55

Means with the same letter in the same column are not significantly different at the 5% threshold

Study of soil organic matter levels based on the number of affected and dead cocoa trees and the number of colonies of mealybugs

The variance analysis revealed no significant differences between soils low in organic matter and soils with acceptable organic matter for the numbers of affected and dead cocoa trees and colonies of Group 1 and 2 mealybug species (Table 19).

Table 19: Comparison of organic matter level based on the number of affected and dead cocoa trees and the number of colonies of mealybug species

Soil type	Number of plants affected	Number of dead plants	Number of Group 1 Mealybug Colonies	Number of colonies of Group 2 mealybugs
Soils with acceptable organic matter	45.62 ± 6.93a	4.50 ± 1.32a	250.75 ± 30.33a	5.50 ± 1.11a
Soils poor in organic matter	81.25 ± 29.30a	1.00 ± 0.57a	275.25 ± 61.68a	15.75 ± 9.85a
P	0,20	0,10	0,79	0,29
Average	57,50	3,33	258,91	8,92
CV	31,25	47,06	20,42	55,34

Averages with the same letter in the same column are not significantly different at the 5% threshold.

Relationship between soil chemical parameters, the number of affected and dead cocoa trees and the number of colonies of mealybug species according to the level of soil organic matter

The Pearson correlation was significant between some parameters following the two soil organic matter levels established in this study.

In soils poor in organic matter, the number of affected cocoa trees (Ncat) and pH (r= 0.97 and P=0.02) and between magnesium content and potassium levels (r= 0.99 and p=0.002) and organic carbon content (r= 0.94 and p=0.04) were significantly and positively correlated. Similarly, in this soil type, the correlation was significant and negative between group 1 and group 2 mealybugs (r=-0.99 and p=0.003) (Table 20).

In soils with acceptable organic matter, significant and positive associations were observed between group 1 mealybugs (Coch1) and potassium (r=0.78 and p=0.02) and magnesium (r=0.77 and p=0.02) levels. Similarly, in this soil type, significant and positive associations were observed between calcium content and pH (r=0.78 and p=0.02) and between magnesium content and potassium content (r=0.94 and p=0.0005) (Table 21).

Table 20: Correlation between the number of affected and dead cocoa trees, soil chemical parameters and the number of mealybug colonies in soils low in organic matter

	pH	Pass	Ca2+	K+	Carbon	Mg2+	Ncat	Ncmort	Coch1	Coch2
pH	1									
Pass	0,13	1								
Ca2+	0,52	0,63	1							
K+	0,49	-0,04	0,74	1						
COS	0,22	-0,36	0,46	0,92	1					
Mg2+	0,45	-0,10	0,70	**0,99***	**0,94***	1				
Ncat	**0,97***	0,3	0,53	0,35	0,04	0,31	1			
Ncmort	-0,64	0,66	0,19	-0,26	-0,30	-0,28	-0,51	1		
Coch1	-0,80	-0,06	-0,77	-0,90	-0,71	-0,88	-0,72	0,46	1	
Coch2	0,80	-0,01	0,72	0,91	0,74	0,89	0,70	-0,51	**-0,99***	1

* Significant correlation at 0.05. MOS= Soil organic matter; Pass= Exchangeable Phosphorus; Ncat = Number of cocoa trees affected; Ncmort = Number of dead cocoa trees; Coch1=Number of colonies of group 1 mealybug species; Coch2= Number of colonies of group 2 mealybug species

Table 21: Correlation between the number of affected and dead cocoa trees, soil chemistry and the number of mealybug colonies in soils with acceptable organic matter

	pH	Pass	Ca2+	K+	Carbon	Mg2+	Ncat	Ncmort	Coch1	Coch2
pH	1									
Pass	0,61	1								
Ca2+	**0,78***	0,89	1							
K+	0,40	0,36	0,38	1						
COS	0,51	0,15	0,57	0,22	1					
Mg2+	0,58	0,61	0,62	**0,94***	0,32	1				
Ncat	-0,06	-0,04	0,03	0,09	0,25	0,09	1			
Ncmort	-0,35	-0,50	-0,39	0,24	0,21	0,14	0,25	1		
Coch1	0,49	0,30	0,33	**0,78***	0,24	**0,77***	0,49	0,26	1	
Coch2	0,46	0,16	0,06	0,19	-0,15	0,30	-0,36	0,13	0,24	1

*Significant correlation at 0.05. MOS= Soil organic matter; Pass= Exchangeable Phosphorus; Ncat = Number of cocoa trees affected; Ncmort = Number of dead cocoa trees; Coch1=Number of colonies of group 1 mealybug species; Coch2= Number of colonies of group 2 mealybug species

Discussion

The results of the variance analysis showed a significant difference between wet and dry seasons for the number of colonies of group 1 mealybug species (*Formicococcus njalensis*, *Planococcus citri* and *Ferrisia. virgata*) in the counties of Bouaflé and Soubré and for the number of colonies of group 2 mealybug species (*Pseudococcus longispinus*, *Phenacoccus hargreavesi*, *Dysmicoccus brevipes* and *Planococcus kenya)* in the department of Bouaflé. However, these results did not show any significant difference between the wet and dry seasons for the number of colonies of Group 1 mealybug species (*Formicococcus njalensis*, *Planococcus citri* and *Ferrisia. virgata*) and for the colony number of Group 2 mealybug species (*Pseudococcus longispinus*, *Phenacoccus hargreavesi*, *Dysmicoccus brevipes* and *Planococcus kenyae*) in the counties of Abengourou and Divo and for the number of colonies of Group 2 mealybug species (*Pseudococcus longispinus*, *Phenacoccus hargreavesi*, *Dysmicoccus brevipes* and *Planococcus kenyae*) in the department of Soubré.

The results of the variance analysis also showed homogeneity between the wet and dry seasons for the number of affected and dead cocoa trees in all the counties.

These results show that rainfall affects mealybug species more than the effects of swollen shoot disease on cocoa trees in the different counties. The influence of the seasons on mealybugs in different localities has been demonstrated by Babin (2023), N'Guettia (2022) and N'Guessan (2021). For these authors, the dynamics of mealybugs vary across the regions and the time of year.

The significant difference between wet and dry seasons for the number of colonies of group 1 and 2 mealybug species in the counties of Bouaflé and Soubré shows a more pronounced effect between these two seasons, which would be mainly due to their more pronounced effects in these localities. On the other hand, the non-significant difference between the wet and dry seasons for the number of colonies of group 1 and 2 mealybug species in the counties of Abengourou and Divo shows a more homogeneous effect between these seasons, which would be mainly due to the slightly pronounced seasonal effects in these localities.

In addition, the effects of swollen shoot disease were the same between the wet and dry seasons in the different departments. This homogeneity would be due to the permanent and irreversible nature of the swollen shoot attacks from one season to another in the same locality.

The results of the Pearson correlation showed that in the dry season, it was significant and positive between group 1 mealybug species and the number of affected and dead cocoa trees and between group 2 mealybug species and the number of dead cocoa trees in the city of Abengourou. These results, in the same season, showed that the correlation was significant and positive between group 2 mealybug species and the number of cocoa trees affected in Bouaflé and between group 1 mealybug species and the number of dead cocoa trees in Divo. On the other hand, the results of the Pearson correlation showed that in the wet season, no link was found between mealybug species and the effects of swollen shoot disease in these counties.

These results show that mealybug species are only related to the effects of swollen shoot disease in the dry season. During this season, cocoa trees are subject to a water deficit that makes them more vulnerable to mealybugs and swollen shoot disease. The variance analysis did not show a significant difference between the dry and wet seasons for mealybug populations and the effects of swollen shoot disease. However, in the dry season, Pearson's correlation showed that mealybugs are linked to the effects of swollen shoot disease, unlike in the wet season. This situation would reflect the importance of water in reducing the impacts of swollen shoot disease in cocoa farms. The same situation was observed by Adja *et al*. (2005) during their study on the influence of climate parameters on mirid populations in Côte d'Ivoire. For these authors, rainfall did not have a direct effect on mirids, whereas a negative and significant correlation was observed between water deficit and mirid populations.

For soil types, the results of the variance analysis showed no significant differences between the clay-sandy and clay-silt soil types for pH, organic matter content, carbon content and nutrient levels of cocoa trees. For the level of organic matter, the results gave rates that varied from 1.79% to 2.68%. Similarly, the results of the variance analysis revealed a significant difference between soils with low organic matter and soils with acceptable organic matter, for organic matter content, carbon content, potassium (K+) and magnesium (Mg2+). On the other hand, they showed homogeneity between these soils, for pH and exchangeable phosphorus and calcium (Ca2+) contents. The results of the variance analysis revealed no significant differences between clay-sandy and clay-silty soil types and between soils with acceptable organic matter and soils low in organic matter, for the number of colonies of group 1 and 2 mealybug species and the number of affected and dead cocoa trees.

These results show that soil texture has no effect on the pH, organic matter, carbon and nutrient content of the cocoa tree. Indeed, the recommended textures in cocoa farming are generally clay-silty and clay-sandy textures (CNRA, 2015; Koko, 2014). However, these types of soils were the ones encountered in this study. They have the same chemical characteristics of soil. Similarly, these results show that soil texture did not influence the effects of swollen shoot disease and mealybug populations. On the other hand, for Tchimou *et al*. (2024), high concentrations of clay can lead to poor water drainage, leading to hypoxic conditions that cause physiological disorders in plants that could explain the appearance of swollen shoot in cocoa farms.

These results also show that the level of soil organic matter influences the levels of organic matter and carbon and the contents of potassium (K^+) and magnesium (Mg^{2+}), but has no effect on the pH and the levels of exchangeable phosphorus (Pass) and calcium (Ca^{2+}). Thus, organic matter would be bound to carbon and chemical elements such as potassium (K^+) and magnesium (Mg^{2+}), unlike calcium (Ca^{2+}) and exchangeable phosphorus (Pass). This situation is due to the low level of organic matter in the soils studied. This organic matter, which constitutes the reservoir of chemical elements in the soil, varied from 1.79% to 2.68%, which is below the minimum rate of 3% required for cocoa cultivation (Hanak *et al*., 2000). These results also show that the level of organic matter, which is related to soil fertility, has no influence on the effects of swollen shoot disease and mealybug populations. For Eraslan *et al*. (2007), soil fertility may affect plant resistance or their ability to tolerate pathogen attacks.

In clay-silt soils, the results of the Pearson correlation showed that it was significant and positive between the number of dead cocoa trees and the sand content. In the same soil type, these results showed that the correlation was significant and negative between the number of dead cocoa trees and the exchangeable phosphorus content and between the number of colonies of group 2 mealybug species and the number of cocoa trees affected. In sandy clay soils, the results of the Pearson correlation showed that it was significant and positive between the number of dead cocoa trees and the potassium (K^+) and magnesium (Mg^{2+}) contents and between the number of colonies of group 2 mealybug species and the number of affected cocoa trees. In soils low in organic matter, the results of the Pearson correlation showed that it was significant and positive between the number of cocoa trees affected and the pH.

These results show that the number of affected cocoa trees and group 2 mealybugs is negatively related in clay-silt soils and positively in clay-sandy soils. Infection of cocoa trees would therefore be caused by group 2 mealybugs. This could be attributed to the ecological characteristics of these mealybug species. Indeed, group 2 mealybugs composed of the species *Pseudococcus longispinus*, *Phenacoccus hargreavesi*, *Dysmicoccus brevipes* and *Planococcus kenyae,* would be more autonomous species with a strong capacity to move within plots (N'Guessan, 2021). These results also show that the number of dead cocoa trees is positively related to the level of sand in clay-silt soils and to the potassium (K^+) and magnesium (Mg^{2+}) contents in clay-sand soils and negatively related to the exchangeable phosphorus content in clay-silt soils. These results also show that the number of affected cocoa trees is positively related to pH in soils poor in organic matter. The mortality of cocoa trees is thought to be due to an excess of sand, potassium and magnesium and a lack of phosphorus in the soil. In addition, the mixed behaviour of soil texture, organic matter and mineral elements shows the degree of degradation of soils affected by swollen shoot disease. According to Pieri (1989), the ability of a soil to retain its chemical fertility or to deteriorate depends on the quantity of reserves that can be mobilised and their transformation into assimilable forms. On the other hand, the work of Zro *et al*. (2024) showed that low phosphorus levels in the soil are the main chemical constraints explaining the onset of swollen shoot disease in cocoa. Similar results were found by Sanogo & Yang (2001) on soybean cultivation. These authors showed that sand content, pH, potassium and phosphorus levels had significant effects on sudden soybean death syndrome. Texture, organic matter and mineral elements are thought to have an influence on swollen shoot disease.

Conclusion

This study highlighted the influence of climate and soil factors and mealybug populations on swollen shoot disease. Indeed, although the variance analysis did not show a significant difference between the dry and wet seasons for the disease effects and mealybug populations, the Pearson correlation highlighted significant links between these variables during the dry season, thus showing the importance of this season in the spread of swollen shoot disease. Similarly, the variance analysis did not show a significant difference between clay-silt and clay-sandy soils and between soils with poor organic matter and those with acceptable organic matter, for the disease effects and mealybug populations. However, the Pearson correlation showed significant links between group 2 mealybugs and the number of affected and dead cocoa trees, between dead cocoa trees and sand content, potassium ($K+$), magnesium ($Mg2+$), and exchangeable phosphorus contents, depending on the textures studied, and between the number of affected cocoa trees and pH in soils poor in organic matter. Thus, the lack of water, texture, organic matter and nutrients for the cocoa tree impacts the progression of swollen shoot disease. These factors can therefore be used for the implementation of an effective fight against swollen shoot disease. This challenge could include the physico-chemical restoration of the soil through appropriate amendments and water supply to cocoa trees during dry periods.

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Data Availability: All data are included in the content of the paper.

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