Effects of cashew tree density on infestations by the wood borer, *Apate terebrans* (Pallas 1772) (Coleoptera, Bostrichidae), in Côte d'Ivoire, West Africa

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Résumé

Apate terebrans (Pallas 1772) affecte considérablement le développement et la productivité des anacardiers (*Anacardium occidentale* Linnaeus 1753) en Afrique de l'Ouest, en forant des galeries à l'intérieur des arbres. La vie cachée de ce ravageur limite l'efficacité des méthodes de lutte par contact, et nécessiterait des méthodes de lutte culturales. Cette étude a évalué les effets de la densité des anacardiers sur les infestations par *A. terebrans*, dans dix vergers de deux zones agro-climatiques (représentées par Bondoukou et Bouna), au nord-est de la Côte d'Ivoire. Dans chaque verger, les anacardiers ont été dénombrés dans 13 quadrats de 400 m², et le nombre d'infestations a été suivi mensuellement sur ces anacardiers, de juin 2018 à juillet 2020. Les indices de Blackman et de Morisita ont été utilisés pour évaluer la distribution des infestations. La densité à Bondoukou, 515 ± 235,5 anacardiers.ha^{-1}, était significativement supérieure à celle de Bouna (235 ± 39,6 anacardiers.ha^{-1}). Cependant, avec un coefficient de variation (CV) de 29,44%, la densité d'anacardiers à Bouna était plus homogène qu'à Bondoukou (CV = 58,64%). Dans les deux zones agro-climatiques, le nombre d'infestations a varié significativement entre les 13 quadrats du verger. Ainsi, la régression linéaire simple a montré que les fortes densités d'anacardiers réduisaient modérément et significativement les infestations. La distribution parcellaire d'anacardiers infestés était agrégée à Bondoukou et aléatoire à Bouna. Des méthodes d'analyses de répartition utilisant la distance entre les plants contribueraient à trouver des distances optimums entre les anacardiers qui limiteraient naturellement les infestations par *A. terebrans*.

Abstract

Apate terebrans (Pallas 1772) affects the development and productivity of cashew trees (*Anacardium occidentale* Linnaeus 1753) in West Africa, by digging galleries inside the trees. The hidden life of this pest limits the effectiveness of contact control methods, and would require cultural control methods. This study assessed the effects of cashew tree density on *A. terebrans* infestations, in ten orchards in two agro-climatic zones (represented by Bondoukou and Bouna), in north-eastern Côte d'Ivoire. In each orchard, cashew trees were counted in 13 quadrats of 400 m^2, and the number of infestations was monitored monthly on these cashew trees, from June 2018 to July 2020. The Blackman and Morisita indices were used to assess the distribution of infestations. The density in Bondoukou, 515 ± 235.5 cashew trees. ha^{-1}, was significantly higher than that in Bouna (235 ± 39.6 cashew trees. ha^{-1}). However, with a coefficient of variation (CV) of 29.44%, the cashew density in Bouna was more homogeneous than in Bondoukou (CV = 58.64%). In both agro-climatic zones, the number of infestations varied significantly among the 13 orchard quadrats. Thus, simple linear regression showed that high cashew tree densities moderately and significantly reduced infestations. The plot distribution of infested cashew trees was aggregated in Bondoukou and random in Bouna. Distribution analysis methods using the distance among plants would contribute to find optimum distances among cashew trees, which would naturally limit infestations by *A. terebrans*.

Keywords: *Anacardium occidentale*, insect pest, spatial distribution, dispersion index, landscape regulation, Bondoukou, Bouna

INTRODUCTION

The cashew tree, *Anacardium occidentale* L. 1753 (Anacardiaceae), is widely cultivated in the tropical countries of Asia and Africa, due to its socio-economic and environmental importance (Balogoun *et al.,* 2014; Ruf *et al.*, 2019). The fruit of cashew nut is mainly used in the food industries (Das & Arora, 2017). Its shell is increasingly used to produce biofuel (Gwoda *et al.*, 2024). In 2020, the United Nations Food and Agriculture Organisation (FAO) estimated that world production of raw cashew nuts amounted to 4,180,000 tonnes harvested from 7,100,000 ha, with West Africa being the main producer (Chen *et al.*, 2023).

In Côte d'Ivoire, the area under cashew trees has increase from around 8,000 ha when this crop was introduced in 1960 as a reforestation plant in the north part of the country, to more than 1,400,000 ha in 2024 (FIRCA, 2024). This dynamic of cashew tree adopting by farmers was largely due to the commercial value of of the cashew nut, but also to the plant's hardiness and low soil and climate requirements (Lautié *et al.*, 2001; Bassett *et al.*, 2018). As a result, cashew is currently the main perennial cash crop in the northern part of the country, thereby contributing for 58% to its agricultural income (Koffi & Oura, 2019). Consequently, since 2015, Côte d'Ivoire has been the world's leading producer of raw cashew nuts, with production of more than 1,000,000 tonnes in 2022 (Ouattara, 2017; FIRCA, 2024).

However, this high production is essentially based on an increased area under cultivation. Indeed, cashew orchards in Côte d'Ivoire are facing a number of major agronomic and phytosanitary constraints (Kouakou *et al.*, 2018; Ouali N'Goran *et al.*, 2020; Soro *et al.*, 2020a), that limit its yields to around 450 kg/ha compared with the 1,200 kg. ha^{-1} at experimental stations (Djaha *et al.*, 2010). Most of the current orchards in Côte d'Ivoire were created on the basis of 'individual' cultivation practices by farmers, without any substantial technical or financial support from the State (Ruf *et al.*, 2019). In this regard, Kambou *et al.* (2019) reported high cashew tree densities, reaching eight (08) times the Ivorian standard of 100 plants. ha^{-1}. According to a study by Soro *et al.* (2020a) carried out in 250 plantations covering 43 cashew-growing localities in Côte d'Ivoire, 98% of orchards have been established by direct sowing, and only 6% of growers thinned their orchards to reach the standard of 100 plants. ha^{-1}. Meanwhile, they observed a significant influence of the diversity of cultural practices on insect damage, but their analyses did not focus specifically on one pest. In addition, several studies (Thomas *et al.*, 2017; Beaumelle *et al.*, 2021) highlighted the influence of the agricultural landscape on the dispersal and abundance of arthropod crop pests.

This study aimed to investigate the relationship between cashew tree density and infestation caused by *Apate terebrans* (Pallas 1772) (Coleoptera: Bostrichidae), one of the main insect pests of cashew trees in West Africa, particularly in Côte d'Ivoire (Agboton *et al.*, 2014; Aliko & Ouali N'Goran, 2022). Adults of this insect can cause the death of 30% of cashew trees, through the galleries that they dig in the sapwood of the tree, and in which they feed and lives (Vasconcelos *et al.*, 2014; Agboton *et al.*, 2017). *A. terebrans* is present in almost all cashew-producing regions in Côte d'Ivoire (Kouadio *et al.*, 2023), and control methods are mainly based on synthetic chemical products (Soro *et al.*, 2020b). Yet, chemical pest control has negative consequences for the environment and human health (Rumschlag *et al.*, 2020). Therefore, alternatives to chemical control, based for example on cultural practices in pest management, are recommended (Onzo *et al.*, 2018; Deguine *et al.*, 2021). However, relatively few studies have been carried out on the relationship between insect damage and planting density, yet they are important for the landscape regulation of insect pests (Lindell *et al.*, 2023). This relationship can be positive in some cases (Yang *et al.*, 2021) and negative in others (Krob *et al.*, 2022), depending in part on the insect's life history. The preliminary study by Yéo *et al.* (2019) in Côte d'Ivoire could be the only one has examined the relationship between *A. terebrans* infestations and cashew tree density. These authors found that high cashew tree density limited infestations of this pest. However, they recommended in-depth studies to attest their results. This justifies the present study. Specifically, i) the cashew tree density was characterised; ii) the effect of cashew tree density was assessed on the level and distribution of *A. terebrans* infestation.

MATERIALS AND METHODS

Sampling sites selection and description
The study was conducted in the localities of Bondoukou and Bouna, approximately 180 km apart, in the northeast of Côte d'Ivoire (**Figure 1**). In Bondoukou, the climate is transitional equatorial, with four seasons: a long and short rainy season from April to June and September to October respectively; a long and short dry season from November to March and July to August respectively. The monthly temperature ranged between 20 - 33 °C, with an annual rainfall of 942 - 1625 mm. The climate in Bouna is wet and dry Sudanese, with one rainy season from March to October and one dry season from November to February. The monthly temperature ranged between 20 - 35 °C,

with an annual rainfall of 992 - 1383 mm (Kouakou *et al.*, 2017). The natural vegetation consists of forest and wooded savannah in Bondoukou, and shrub and tree savannahs in Bouna (Guillaumet & Adjanohoun, 1971).
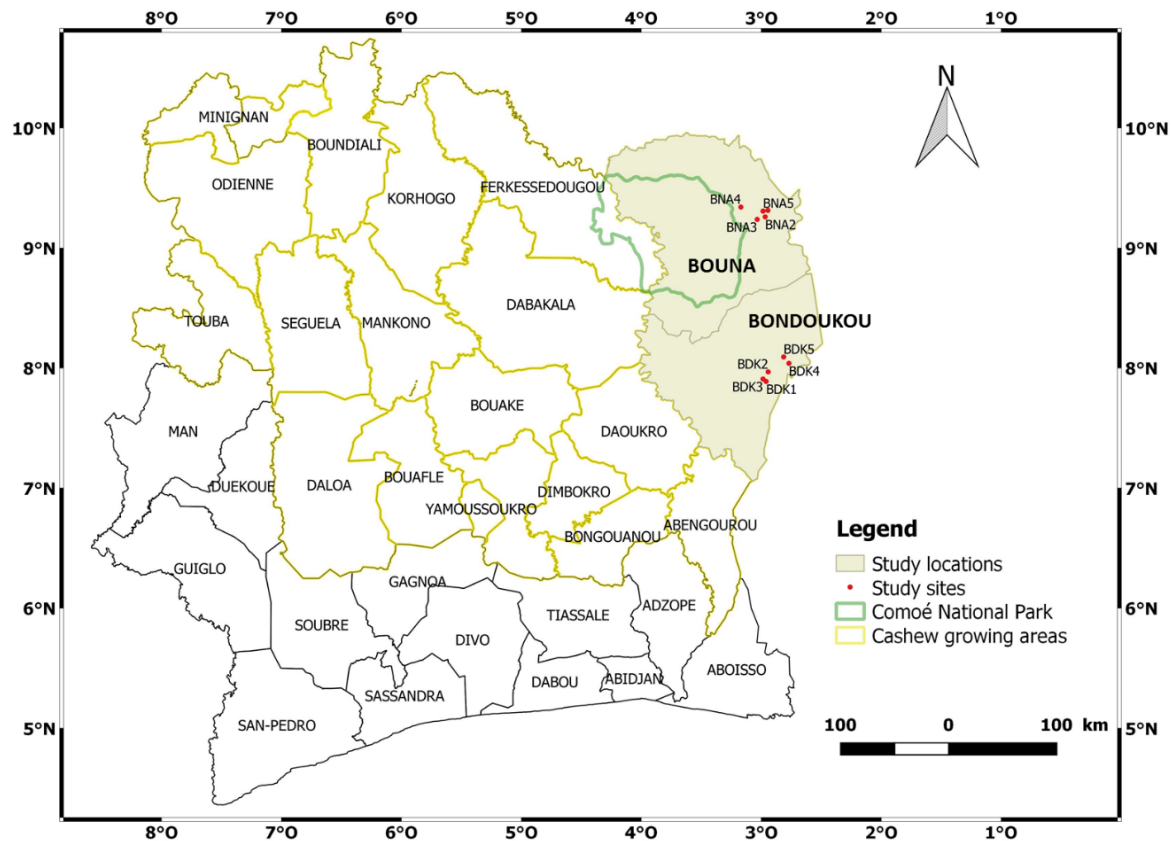

Figure 1: Map of Côte d'Ivoire showing the study location

In each locality, five study sites of at least 2 ha in size, 15 to 20 years old, infested by *A. terebrans* but not subject to chemical insecticide applications (at least two years prior to the study) were selected. All these sites were planted in bulk by direct sowing, using unimproved seeds. The systematic sampling using quadrats was used because it allows the density and heterogeneity of cashew trees to be assessed. This sampling method is also used to assess the spatial distribution of *A. terebrans* infestations and the effect of cashew tree density on these infestations. In each site, a plot of 100 m x 100 m (i.e., 1 ha) was delimited, starting from an edge. This plot was then subdivided into 13 quadrats of 20 m x 20 m (i.e., 400 m^2) at 20 m intervals. All cashew trees in the 13 quadrats were then numbered, marking a total sample of 1924 cashew trees in both localities. Distance between two study sites was approximately 2.5 to 30 km, and each of them was geo-referenced by Global Positioning System (**Table 1**).

Table 1: Geographical coordinates and age of the study sites

Location	Study sites	Geographical coordinates			Age (years)
		Latitude	Longitude	Altitude (m)	
Bondoukou	BDK1	7°53.344'N	2°57.560'W	299	15
	BDK2	7°54.623'N	2°59.064'W	275	17
	BDK3	7°58.111'N	2°56.537'W	304	15
	BDK4	8°05.546'N	2°48.778'W	394	16
	BDK5	8°02.396'N	2°46.112'W	376	18
Bouna	BNA1	9°15.655'N	2°58.037'W	286	15
	BNA2	9°18.845'N	2°56.686'W	370	15
	BNA3	9°20.535'N	3°10.209'W	329	17
	BNA4	9°14.337'N	3°02.023'W	267	17
	BNA5	9°18.480'N	2°59.085'W	345	15

Assessment of cashew density

Cashew density is the ratio of the total number of cashew trees in a quadrat to the area of that quadrat. The density of cashew trees in each quadrat was determined by counting the cashew trees in the 13 quadrats of each study site, i.e., a total area of 0.52 ha. The density per hectare was determined by extrapolation. The variation in the number of cashew trees among the 13 quadrats of each study site was assessed using the coefficient of variation (CV):

$$CV = \frac{\sigma}{\mu}$$

With σ and μ representing the standard deviation and the mean of the number of cashew trees per quadrat of a study plot, respectively.

Counting *A. terebrans* infestations

Given the cryptic life of *A. terebrans*, the monitoring of its infestations was done through the galleries bored inside the cashew tree (Agboton *et al.*, 2017). The presence of the insect inside the cashew tree is characterised by the presence of fresh sawdust from the cashew wood at the gallery opening, known as the 'fresh entry hole (FEH)', and under the infested cashew tree (**Figure 2**).

Thus, in this study, a FEH is equivalent to one infestation of *A. terebrans*. For two consecutive years, from July 2018 to June 2020 (i.e., two cashew production seasons), the 1924 marked cashew trees were inspected once at the end of each month, in order to count all the FEH present on each infested cashew tree.
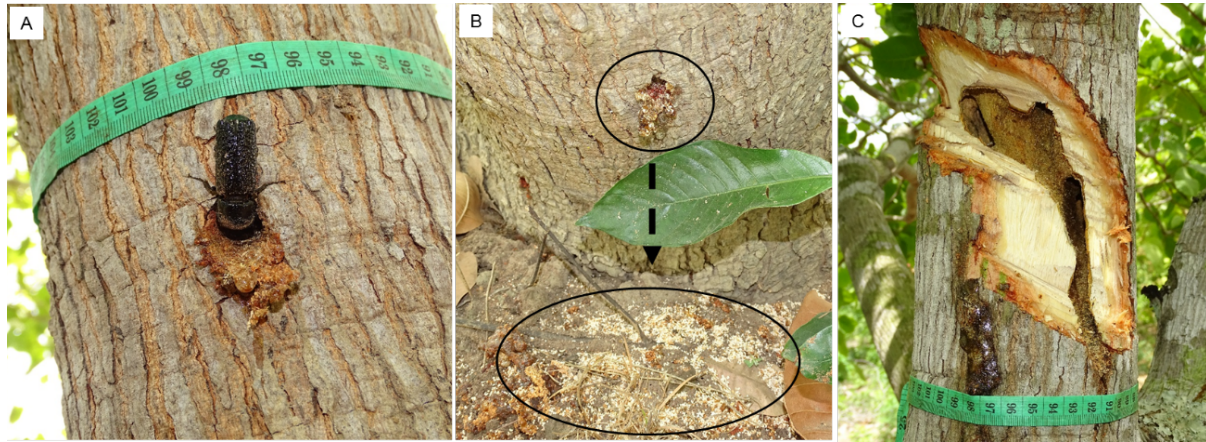
Figure 2: Illustration of *Apate terebrans* infestations on a live cashew tree. (A) *A. terebrans* at the entrance to the fresh hole; (B) Sawdust under an infested cashew tree; (C) Gallery of *A. terebrans*

Assessment of the spatial distribution of cashew trees infested by *A. terebrans*

The contiguous quadrat method was used to analyse the spatial distribution of infested cashew trees at plot level (Agbangla *et al.*, 2015). This method is based on the examination of the mean and variance of the number of infested cashew trees per quadrat (Jayaraman, 1999). The type of distribution of infestations (aggregate, regular or random) was determined using the Blackman (DI_B) and Morisita (DI_M) dispersion indices (Amaral *et al.*, 2014; Agbangla *et al.*, 2015; Hayes & Castillo, 2017). The simultaneous use of these two indices aimed at confirming the result obtained by each of the two indices.

$$DI_B = \frac{s^2}{\mu}$$

With s^2 and μ representing the variance and mean of the number of infested cashew trees per quadrat, respectively, in each study site.

$$DI_M = n\left(\frac{\sum X^2 - N}{N(N-1)}\right)$$

With n: total number of quadrats; X: number of infested cashew trees in a single quadrat; $\sum X^2$: sum of all X^2 values; N: total number of infested cashew trees in the 13 quadrats of each study site. For both dispersion index models, DI values greater than 1 indicate that the distribution of infestation is aggregated, while DI values less than 1 indicate a regular distribution of infestation. The distribution is random when DI = 1 (Canard & Poinsot, 2004).

Collection of climatic data

Two thermo-hygrometers (EasyLob EL-USB-2) installed in each area, close to the study sites, were used to simultaneously record temperature and relative air humidity during the study.

Data analysis
The collected data were processed and analysed using Excel 2013 and RStudio 3.6.2 (Rstudio Team, 2019).
The coefficient of variation was used to determine the variation in the number of cashew trees among the 13 quadrats in each study site. Kruskal Wallis test was used, after verification of normality (Shapiro's test) and homogeneity of variances (Bartlett's test), to compare cashew tree densities of the different study sites in each locality. Wilcoxon post hoc test was used for pairwise comparisons. For the comparison of this variable between the two localities, the student's t-test was used, after testing for normality (Shapiro's test) and homogeneity of variance (Levene's test).

Kruskal Wallis test was also used to compare the average number of *Apate terebrans* infestations of the different study sites in each locality, considering the quadrat as a replicate. For each study site, the proportions of infestations in the 13 quadrats were compared using Fisher's test, after verification of Cochran's rule.

Simple linear regression was used to assess the effect of cashew tree density on infestation by *A. terebrans*. To do this, cashew tree densities of the 13 quadrats of each study site were related to the infestations counted in these quadrats. However, in order to limit the influence of the shade of large trees (other than cashew trees), the quadrats in which they were located were not used in this analysis. Thus, in one study site, the maximum number of quadrats not taken into account was three.

The Chi-square test (χ^2) for $\alpha = 5\%$ was used to test whether the dispersion indices values are significantly different from 1 (random dispersion), considering:

$$\chi2 \, (\mathrm{d.f.}) \; = \frac{(q-1)s^2}{\mu}$$

With d.f. (degree of free) = $q - 1$, q being the number of quadrats in each study site, s^2 and μ representing the variance and the mean number of infested cashew trees per quadrat in each study site, respectively (David & Moore, 1954).

RESULTS

Cashew tree densities
The average cashew tree density varied significantly among the five study sites in each area (d.f. = 4; $p < 0.01$) (**Figure 3**). A mean ($\pm$ standard deviation) of 515 ± 235.5 cashew trees. ha^{-1} was obtained in Bondoukou, which was significantly higher than the density of 235 ± 39.6 cashew trees. ha^{-1} in Bouna.
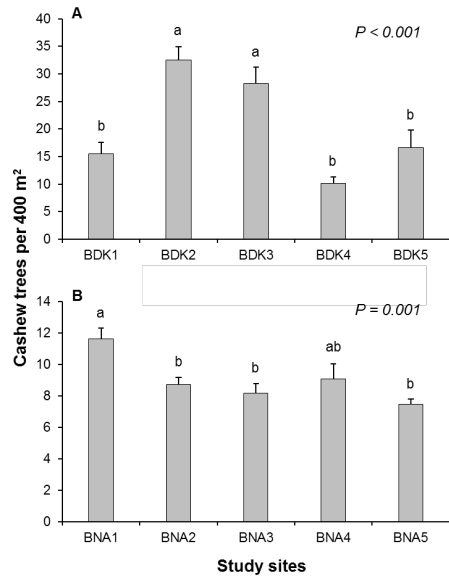
Figure 3: Average (± SD) density of cashew trees within the 400 m^2 quadrats of study sites in Bondoukou (A) and Bouna (B) during the 2018 to 2020 production seasons in Côte d'Ivoire. Significant differences are indicated by different letters (*p* < 0.05)
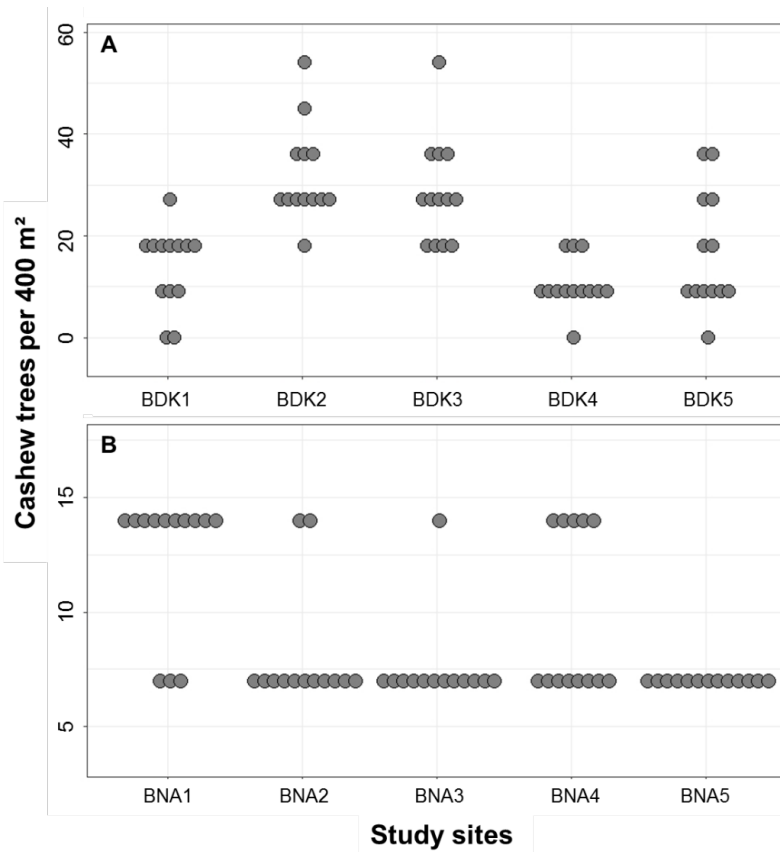

Figure 4: Variation in the number of cashew trees within the 13 quadrats in the study sites in Bondoukou (A) and Bouna (B) during the 2018 to 2020 production seasons in Côte d'Ivoire

Abundance of *A. terebrans* infestations

In each locality, the number of infestations varied significantly among the five study sites (**Figure 5**). In Bondoukou, mean (± standard deviation) of 99.2 ± 37.4 infestations and 14 ± 3.87 infested cashew trees (ICTs) per study site were observed in the first sampling year, compared with 73.8 ± 45.85 infestations and 7.2 ± 2.95 ICTs per study site in Bouna, during the same period. In the second year of sampling, the means were 101 ± 47.88 infestations and 9.8 ± 7.39 ICTs in Bondoukou, and 61 ± 57.76 infestations and 6.4 ± 6.54 ICTs in Bouna.

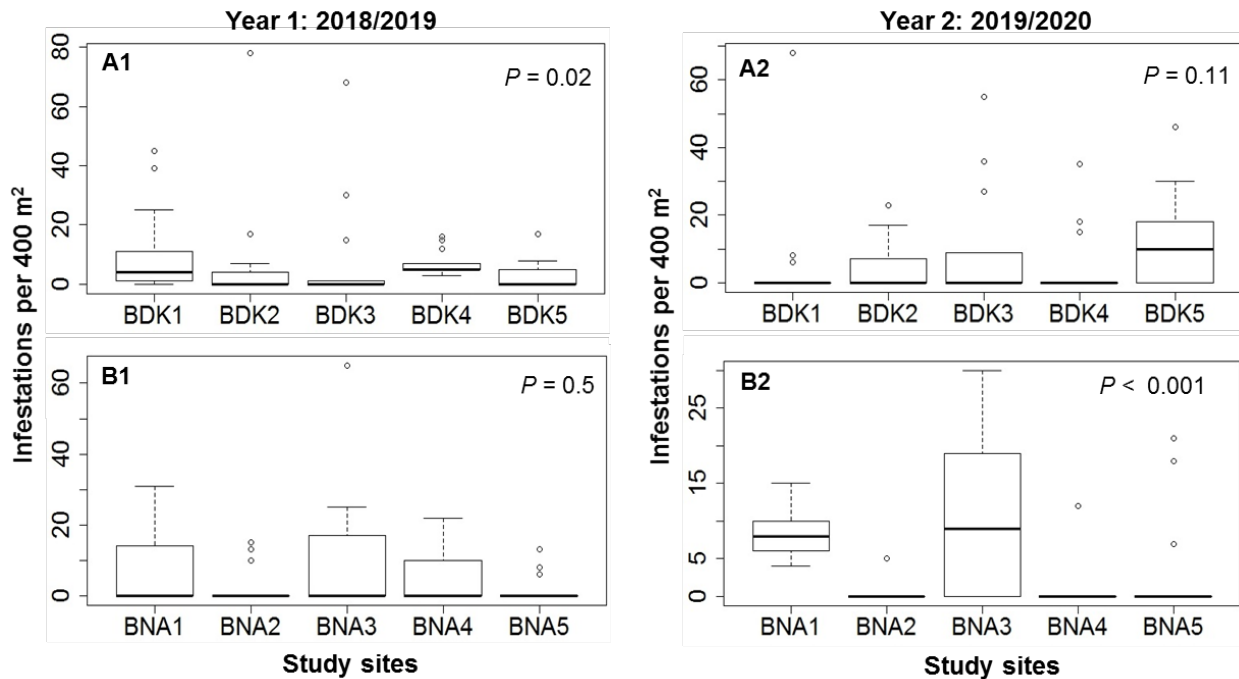**Figure 5:** Comparison of infestation abundance among study sites in Bondoukou (A1, A2) and Bouna (B1, B2) during two cashew crop seasons (2018/2019 and 2019/2020) in Côte d'Ivoire

The proportion of infestations varied very significantly between the 13 quadrats at each study site in Bondoukou and Bouna (d.f. = 12; $p < 0.0001$). This proportion varied from 0 to 100% for one quadrat (**Table 2**).

Table 2: Comparison of proportions of *Apate terebrans* infestation in the 13 quadrats of each study site in Bondoukou and Bouna during two cashew cropping seasons (2018/2019 and 2019/2020) in Côte d'Ivoire

Location	Study sites	Proportion of infestation (%) in the 13 quadrats of each study site												
		1	2	3	4	5	6	7	8	9	10	11	12	13
		Year 1: July 2018 to June 2019												
Bondoukou	BDK1	0.3 a	0 a	0 a	2.1 ab	2.9 ab	0.4 a	32.1 d	3.6 ab	27.9 cd	7.9 abc	0 a	4.3 ab	17.9 bcd
	BDK2	3.6 a	70.3 b	0 a	0 a	2.7 a	0 a	0 a	0 a	15.3 a	6.3 a	0 a	1.8 a	0 a
	BDK3	0 a	59.6 c	0 a	0.9 a	26.3 b	0 a	0 a	0 a	0 a	0 a	0 a	13.2 ab	0 a
	BDK4	7.7 a	6.6 a	5.5 a	17.6 a	5.5 a	13.2 a	6.6 a	5.5 a	3.3 a	5.5 a	3.3 a	3.3 a	16.5 a
	BDK5	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a	42.5 b	12.5 ab	5 ab	20 ab	20 ab
Bouna	BNA1	16.8 ab	6.9 ab	27.7 b	13.9 ab	0 a	30.7 b	0 a	0 a	0 a	0 a	0 a	4 a	0 a
	BNA2	26.3 ab	0 a	0 a	0 a	39.5 b	0 a	0 a	0 a	0 a	0 a	34.2 ab	0 a	0 a
	BNA3	0 a	0 a	0 a	0 a	0 a	17.4 b	47.1 c	18.1 b	12.3 ab	0 a	0 a	5.1 ab	0 a
	BNA4	18.5 abc	0 a	29.2 bc	33.8 c	0 a	0 a	0 a	0 a	3.1 ab	0 a	0 a	0 a	15.4 abc
	BNA5	29.6 ab	48.1 b	22.2 ab	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a
		Year 2: July 2019 to June 2020												
Bondoukou	BDK1	0 a	0 a	0 a	7.3 a	0 a	0 a	82.9 b	0 a	0 a	0 a	0 a	9.8 a	0 a
	BDK2	13 ab	13 ab	0 a	0 a	31.5 b	42.6 b	0 a	0 a	0 a	0 a	0 a	0 a	0 a
	BDK3	41.4 c	27.1 c	0 a	6.8 ab	20.3 bc	0 a	0 a	0 a	0 a	0 a	0 a	4.5 ab	0 a
	BDK4	51.5 b	22.1 ab	26.5 b	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a
	BDK5	0 a	0 a	0 a	8.9 abcd	4.8 abc	3 ab	0 a	15.5 bcd	10.7 abcd	27.4 d	6 abc	17.9 cd	6 abc
Bouna	BNA1	9.1 a	8.2 a	10.9 a	6.4 a	5.5 a	13.6 a	7.3 a	4.5 a	3.6 a	11.8 a	4.5 a	6.4 a	8.2 a
	BNA2	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a	100 b	0 a	0 a	0 a	0 a
	BNA3	2.3 ab	0 a	15.8 bc	11.3abc	0 a	0 a	20.3 c	6.8 abc	14.3 bc	0 a	22.6 c	0 a	6.8 abc
	BNA4	0 a	100 b	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a
	BNA5	0 a	0 a	0 a	0 a	0 a	0 a	0 a	15.2 ab	39.1 b	0 a	45.7 b	0 a	0 a

The proportions in lines followed by the same letter do not differ at the 5% level (Fisher's test)

Effect of cashew tree density on the abundance of *A. terebrans* infestations
Linear regression analysis showed that high cashew density negatively influenced infestation abundance ($p < 0.05$) in both localities. The relationship between these two variables was moderate and significant for four study sites in Bondoukou (BDK1, BDK2, BDK3 and BDK4) and two study sites in Bouna (BNA1 and BNA3). However, for a given site, the relationship between cashew tree density and infestation abundance was only significant for the first year of sampling (**Table 3**)

Table 3: Relationship between cashew tree density and the abundance of *Apate terebrans* infestations in Bondoukou and Bouna during two cashew cropping seasons (2018/2019 and 2019/2020) in Côte d'Ivoire

Location	Study sites	Regression parameters			
		Linear regression	**R^2**	***p*-value**	**d.f.**
		Year 1: July 2018 to June 2019			
Bondoukou	BDK1	y = - 1.54x + 35.37*	0.52	0.02	8
	BDK2	y = - 1.32x + 50.90*	0.46	0.02	9
	BDK3	y = - 0.88x + 36.11*	0.55	0.05	9
	BDK4	y = - 0.76x + 14.69*	0.53	0.005	11
	BDK5	y = - 0.17x + 06.71	0.30	0.08	9
Bouna	BNA1	y = - 1.98x + 31.99	0.15	0.21	10
	BNA2	y = 0.65x - 02.40	0.03	0.57	10
	BNA3	y = - 3.75x + 42.54	0.13	0.28	9
	BNA4	y = 1.34x - 7.16	0.29	0.09	9
	BNA5	y = 1.33x - 7.88	0.11	0.29	10
		Year 2: July 2019 to June 2020			
Bondoukou	BDK1	y = - 1.75x + 32.93	0.33	0.08	8
	BDK2	y = 0.21x - 1.53	0.03	0.58	9
	BDK3	y = - 0.48x + 26.04	0.08	0.40	9
	BDK4	y = - 0.2x + 7.21	0.01	0.80	11
	BDK5	y = 0.61x + 4.34	0.28	0.09	9
Bouna	BNA1	y = - 1.26x + 23.40*	0.68	0.001	10
	BNA2	y = 0.26x - 1.78	0.18	0.17	10
	BNA3	y = - 4x + 40*	0.58	0.007	9
	BNA4	y = 0.17x - 0.58	0.04	0.57	9
	BNA5	y = 2.26x - 13.29	0.10	0.31	10

The equation is given by y = ax + b, where y is the abundance of infestations, x is the cashew density factor, a is the directing coefficient and b is the intercept. *Asterisks indicate a significant regression at the 5% level

Effect of cashew tree density on the spatial distribution of *A. terebrans* infestations
The plot distribution of infestations by *A. terebrans* was aggregated in both areas. The distribution of infested cashew trees (ICTs) varied from one study site to another. In Bondoukou, three aggregative, one random and one regular distributions of ICTs were observed in each year ($p < 0.05$). In contrast, no site had an aggregative distribution in Bouna (**Table 4**). At the locality scale, the distribution of ICTs was aggregative in Bondoukou (Year 1: $DI_B = 1.49$; $DI_M = 1.40$; $Chi^2 = 81.88$; Year 2: $DI_B = 2.41$; $DI_M = 2.62$; $Chi^2 = 132.71$; with d.f. = 55; $p = 0.05$). In Bouna, the distribution was random (Year 1: $DI_B = 1.30$; $DI_M = 1.56$; $Chi^2 = 74.13$; Year 2: $DI_B = 1.15$; $DI_M = 1.21$; $Chi^2 = 65.44$; with d.f. = 57; $p = 0.05$).

Table 4: Distribution indices of cashew trees infested by *Apate terebrans* in Bondoukou and Bouna during two cashew cropping seasons (2018/2019 and 2019/2020) in Côte d'Ivoire

Location	Study sites	Distribution indices				
		DI_B	DI_M	d.f.	Chi^2	Repartition
		Year 1: July 2018 to June 2019				
Bondoukou	BDK1	1.18	1.10	9	10.64	Random
	BDK2	2.52	2.02	10	25.25	Aggregative
	BDK3	1.91	2.14	10	19.11	Aggregative
	BDK4	0.12	0.25	12	1.46	Regular
	BDK5	2.2	2.2	10	22	Aggregative
Bouna	BNA1	1.45	1.45	11	16	Random
	BNA2	1.51	2.4	11	16.6	Random
	BNA3	0.87	0.73	10	8.67	Regular
	BNA4	1.40	1.57	10	14	Random
	BNA5	1.51	2.4	11	16.6	Random
		Year 2: July 2019 to June 2020				
Bondoukou	BDK1	1.22	1.66	9	11	Random
	BDK2	1.95	2.36	10	19.5	Aggregative
	BDK3	3.01	2.68	10	30.15	Aggregative
	BDK4	0.83	0	12	10	Regular
	BDK5	2.04	1.58	10	20.38	Aggregative
Bouna	BNA1	0	0	11	0	Regular
	BNA2	0.91	0	11	10	Regular
	BNA3	1.6	1.6	10	16	Random
	BNA4	1.53	3.67	10	15.33	Random
	BNA5	1.51	2.4	11	16.6	Random

DI_B and DI_M: respectly Blackman and Morisita dispersion indices

Climatic conditions

The average (± standard deviation) monthly temperatures during years 1 and 2 were 29.28 ± 1.79 °C and 27.70 ± 1.84 °C in Bondoukou, compared to 30.30 ± 1.71 °C and 29.30 ± 1.98 °C in Bouna. Those of hygrometry were 65.93 ± 12.69% and 71.16 ± 14.09% in Bondoukou, against 52.18 ± 24.68% and 58.26 ± 22.82% in Bouna.

DISCUSSION

The significant differences between cashew densities are mainly due to the implementation of a 'national cashew thinning programme' by farmers in Bouna as opposed to Bondoukou. This programme, initiated by the government of Côte d'Ivoire, aims at reducing cashew trees density in the orchards to a standard of 100 cashew trees. ha^{-1}, which would optimise the yield of the orchards (FIRCA, 2024). The application of this programme therefore creates a certain homogeneity of cashew tree density at plot level, which is reflected in a low coefficient of variation in Bouna, unlike in Bondoukou. Furthermore, the wide variation in cashew density within the original

orchards, as is the case in Bondoukou, is mainly the result of the historical context of the establishment of the crop. Ivorian orchards were generally created in bulk, without staking, and with a view to protecting the environment (Ruf *et al.*, 2019). This patch heterogeneity is known to influence insect dynamics (Alford *et al.*, 2018; Snyder *et al.*, 2021).

We believe that relative humidity is relatively higher in high-density cashew quadrats than in low-density ones, as reported by Yang *et al.* (2021) in China. They have observed that the high rice density created a relatively humid microclimate that was more favourable to leafhoppers and planthoppers. The low abundance of *A. terebrans* in high-density cashew quadrats would be justified by the negative effect of humidity on bostrichids (Nansen *et al.*, 2002; Hodges *et al.*, 2003), in particular on *A. terebrans* (Aliko & Ouali N'Goran 2022). Similar results were obtained by Krob *et al.* (2022) in Philippines, who showed that high cotton density reduced trips damage. In addition, bostrichids prefer wood with relatively low moisture content (Ivie, 2002; Cookson, 2004). Several authors (Thackeray *et al.*, 2016; Falk *et al.*, 2018) have shown a direct and/or indirect (e.g., physiological changes in the host plant) influence of climatic and biotic factors on the temporal dynamics of insects. Furthermore, in the present study, the relationship between cashew tree density and infestations by *A. terebrans* was found to be influenced by other factors, including the border effects in the high cashew density quadrats. Indeed, a large number of infestations were sometimes recorded at the edge of these quadrats, especially when they were contiguous to low cashew density quadrats, or when the edge of these quadrats was less shaded. The border effects on insects have been mentioned by Amala & Shivalingaswamy (2018). Otherwise, the weak relationship observed between *A. terebrans* infestations and cashew tree density during the second year of sampling could be justified by the induced defences of infested cashew trees in the first year of sampling (Boone *et al.*, 2011; Goiana *et al.*, 2019). Indeed, it was observed that 74% of cashew trees attacked by *A. terebrans* in the first year of sampling were no longer attacked in the second year. This observation is in accordance with Agboton *et al.* (2017) had made the same observation. In addition, given that there are different cashew varieties within each study site, the preference of one variety could influence the relationship between cashew density and infestation (Schröder *et al.*, 2015; Reisenman *et al.*, 2016).

An aggregated distribution of *A. terebrans* infestations was observed in the study sites in both localities, as reported by Agboton *et al.* (2017) in cashew orchards in Benin. This type of distribution is known for several bostrichids such as *Prostephanus truncatus* (Horn 1878) and *Rhyzopertha dominica* (Fabricius 1792) (Nansen *et al.*, 2002; Steel *et al.* 2012). According to Jayaraman (1999), Canard & Poinsot (2004), several causal mechanisms, such as environmental heterogeneity, gregarious behaviour and breeding mode, could explain such a distribution. For example, it has been reported that *R. dominica* males release two aggregation pheromones, Dominicalure-1 and Dominicalure-2, which attract conspecifics to located food resources (Bashir *et al.*, 2003; Edde *et al.*, 2007). As for the distribution of cashew trees infested by *A. terebrans*, it was globally aggregated in Bondoukou and random in Bouna. These two different types of distribution would be the result of the plot structure of the cashew trees. Indeed, the heterogeneity of plots within the plot influences the dynamics of crop pest (Wang *et al.*, 2023). Therefore, the large heterogeneity of cashew trees observed in Bondoukou would strongly justifies the aggregative distribution of infested cashew trees. The insect mainly attacks cashew trees in quadrats characterised by a low density of wood. In Bouna, the microclimate being relatively homogeneous, the spatial barrier appears reduced for the pest. As a result, the pest is dispersed throughout the plot in a more or less homogeneous manner. These results confirm those of Yéo *et*

al. (2019) on the spatial distribution of cashew trees infested by *A. terebrans* in Bondoukou and Bouna, in Côte d'Ivoire.

CONCLUSIONS

This study showed a large heterogeneity in cashew tree density in Bondoukou and Bouna (northeast of Côte d'Ivoire), which significantly influenced the abundance and patchy distribution of *A. terebrans* infestations. We recommend that entomological studies in cashew orchards planted in bulk take into account the existence of heterogeneity in cashew tree density and its probable influence on insects. Further studies should be carried out to determine the optimum spacing among cashew trees, as well as on the varietal resistance of cashew trees, with a view to sustainably controlling *A. terebrans* infestations and improving cashew tree productivity.

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