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Natural regulation and bioecology of *S. frugiperda* (J.E. Smith, Lepidoptera Noctuidae) in maize crops in Senegal

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Abstract

Spodoptera. frugiperda is a major invasive insect pest native to tropical and subtropical regions of the Americas. It was first reported in the African continent in 2016, specifically in West Africa: Nigeria, Sao Tomé, Benin and Togo In early 2017, the species invaded sub-Saharan African countries, including Senegal. The study aimed to identify the natural enemies of *S. frugiperda* in three maize-growing areas in Senegal. A survey was carried out to explore the natural enemies of the fall armyworm and assess the level of parasitism in three maize-growing areas in Senegal. Nine maize fields of smallholders previously surveyed were selected in three regions including Kaolack, Kaffrine and Tambacounda. A total of 1258 larvae were collected, of which 523 were attacked by parasitoids and entomopathogens, representing an average incidence of 41.57%. Two orders of parasitoid insects were extracted from armyworm larvae and pupae, divided into eight families and one unidentified family. 159 individuals emerged in the laboratory, including 6 species of Ichneumonidae, 18 of Braconidae, 2 Evanidae, 3 Scoilidae, 124 Tachinidae, 4 Syrphidae, 1 Sphecidae and 1 of unidentified family. Parasitism caused by entomopathogenic nematodes was highest in the Kaolack region, followed by Kaffrine and Tambacounda. In contrast to parasitoids, the highest levels of parasitism were noted respectively in the Tambacounda, Kaffrine and Kaolack regions. Although the armyworm spread rapidly in the production sites, the results of the study showed a reasonable level of biological control, especially by Diptera.

Keywords: *Spodoptera frugiperda,* natural enemies, maize, parasitism, entomopathogen

Introduction

Native to the Central American countries of Mexico, Guatemala, Peru and Bolivia, corn is a very old tropical plant. Also known by its scientific name Zea mays, it was introduced to Europe in the 16th century. Portuguese explorers reported its presence in Africa in the Sudanian zone in the 17th century. Maize was the staple food of the ancient civilizations of Central America, where it originated. Maize (Zea mays L.) is an annual herbaceous plant consisting of a single, large-diameter culm made up of a pile of nodes and internodes. It is widely grown as a cereal for its starch-rich grains and represents the leading cereal production (1235.73) ahead of rice 513.54 and wheat 784.91 metric tons (Shahbandeh, 2024) [40]. However, its production isthreatened by the fall armyworm, *Spodoptera frugiperda* (J.E.Smith) (*Lepidoptera*: Noctuidae). *S. frugiperda,* native to Latin America, is a highly polyphagous pest that attacks both cultivated plants and weeds (Casmuz *et al.*, 2010) [6]. This invasive pest was first reported in West Africa in late 2016 (Day *et al.*, 2017; Germain *et al.*, 2017; Goergen *et al.*, 2016) [9, 14, 16]. In early 2017, *S. frugiperda* invaded sub-Saharan African countries, including Senegal (Brévault *et al.*, 2018b) [5]. Recent studies have confirmed the presence of the fall armyworm in 44 African countries (Prasanna *et al.*, 2018; Rwomushana *et al.*, 2018). More recently, *S. frugiperda* has been observed in China and Australia (IPPC, 2020; Li *et al.*, 2020; Wang *et al.*, 2020) [34, 49]. It currently exists in two strains, the strain attacking rice crops and the strain attacking growing maize, where molecular studies have demonstrated their presence in Africa (Day *et al.*, 2017; Gichuhi *et al.*, 2020; Nagoshi *et al.*, 2017) [9, 15]. *Spodoptera frugiperda* is a devastating pest with a great Capacity to spread on the African continent. It thus causes economic damage in various crops such as maize, sorghum, sugarcane, beans and cotton, and notably threatens the food security of millions of people (Day *et al.*, 2017; Sharanabasappa *et al.*, 2018) [9, 42]. In Brazil, it has been reported that *S. frugiperda* can cause damage of up to 34% reduction in grain yield, resulting in annual losses of nearly $400 million. According to Day *et al.* (2017) [9] and Toepfer *et al.* (2019) [48] the annual losses caused in Africa by *S. frugiperda* in the absence of effective control methods for the 12 largest maize producers range from 8.3 to 20.6 million tonnes of maize each year. Also in Africa, according to FAO 2018, *S. frugiperda* can cause up to $4.8 billion in economic losses to maize production. Although it is widely accepted as one of the most damaging crop pests in the Americas, economic losses and control costs are not comprehensive, and the use of chemical insecticides remains common practice. In addition to these economic losses and the rapid expansion of the armyworm, only synthetic insecticides are used as an emergency measure to mitigate the pest's distribution and reduce damage in corn fields (Prasanna *et al.*, 2018). However, other means of control desired for integrated management are disrupted by the effects of synthetic insecticides (Day *et al.*, 2017) [9]. The use of insecticides can eliminate beneficial insects (auxiliaries), whereas this biodiversity is essential for biological control.

Furthermore, it has been shown that frequent pesticide use can lead to adaptation by pests, which develop resistance mechanisms to chemical insecticides including pyrethroids, carbamates, neonicotinoids, organophosphates and biopesticides such as Bacillus thuringiensis (BT). Therefore, it is preferable to mitigate the use of synthetic insecticides, especially broadspectrum ones, by promoting proven and sustainable IPM technologies against *S. frugiperda* (Kenis *et al.*, 2019) [20] that also meet the needs of small-scale African farmers. The use of biopesticides based on plant extracts such as neem Azadirachta indica (Meliaceae) against fall armyworm may be an alternative control option (Adeye *et al.*, 2018; Bateman *et al.*, 2018; Midega *et al.*, 2018; Shaiba *et al.*, 2019; Tepa-Yotto *et al.*, 2021; Tepa-Yotto *et al.*, 2022) [1, 2, 23, 41, 45, 48]. However, standardized biopesticides are not sufficiently available or are expensive compared to synthetic insecticides. Another alternative is the use of biological control agents or natural enemies. This is a cost-effective, environmentally friendly approach that has been used against fall armyworm in the Americas (Hruska, 2019) [18]. However, developing a biological control approach requires in-depth knowledge of crops and cropping systems, as well as existing natural enemies.

The general aim of this study is therefore to identify the natural enemies of *S. frugiperda* in maize-growing areas in Senegal and their level of parasitism.

Materials and methods

Presentation of the study area

The study framework for this theme is located in three agro-ecological zones of Senegal: the center and souther basin groundnut and the eastern oriental Senegal, the main corn production areas. These three areas are characterized as agro-ecological zones on the basis of three physical criteria: climate, rainfall and soil type. Both are historically agricultural zones. The groundnut basin is characterized by the predominance of soils that are not very suitable for growing maize, and partly encloses the Kaolack and Kaffrine regions. Geomorphologically, three main soil types characterize the groundnut basin: leached tropical ferruginous soils or Dior with sandy characteristics (70%), hydromorphic soils or Deck, clayey (10%) and sandyclay soils or Deck-Dior (20%) (Diatta *et al.*, 2017) [11]. It is swept by a Sudanian-type climate and is characterized by a long dry season (November to May) and a short rainy season (June to October) (Faye, 2010) like the Dakar region. Central eastern Senegal is an area with significant agricultural potential for the development of crops such as maize and cotton, as well as groundnuts, millet and sorghum (Ndiaye *et al.*, 2005). It is characterized by its Sahelo-Sudanian climate, with two alternating seasons. To carry out sampling in crop plots in the target zones, we selected the sites whose geographical coordinates are shown below:

Table 1: Geographical coordinates by study sites

Regions	Localities	Agro-ecological area	Geographic coordinates
Tambacounda	Ngolol-keba	Sénégal oriental	N13°42'123’’ W14°06'601’’
	Dane-Niacko		N13°47'865’’ W14°08'367’’
	Sare-sambourou		N13°54'231’’ W14°03'640’’
Kaffrine	Taïf	Centre bassin arachidier	N14°13'815’’ W15°31'959’’
	Ndjigui		N14°13'815’’ W15°31'959’’
	Ndiognick		N14°01'829’’ W15°38'155’’
Kaolack	Mbiteyene	Sud bassin arachidier	N13°44'109’’ W15°56’’477’’
	Keur ousmane Ndiamatou		N13°50’17’’ W15°52’51’’
	Keur abibou Niass		N13°44'939’’ W15°50'986’’

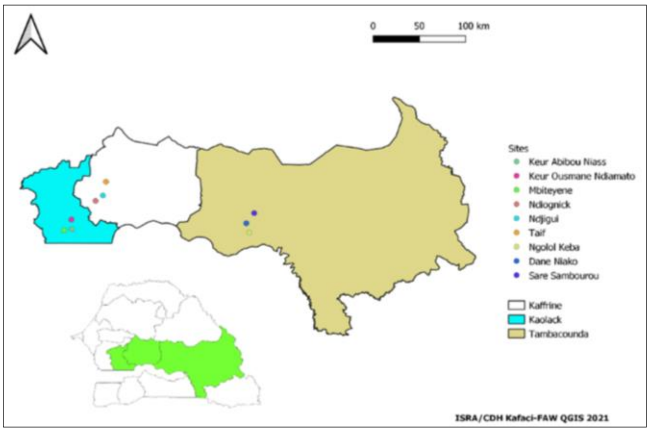

Fig 1: Location map of study sites

Larval sampling

Informations and data for the study were collected through field missions carried out during two production seasons (July and September) in 2021 and 2022). More specifically, these missions took place in three regions of Senegal: Kaolack, Kaffrine and Tambacounda, thus covering two different agro-ecological zones. In each of these three regions, three sites were surveyed, for a total of nine. The methodology consisted in collecting a large number of *S. frugiperda* caterpillars according to a W diagram (Prasanna *et al.*, 2018) across the different sites. Collection also consider the phenological stages of the maize plant (early whorl stage, advanced whorl stage, flowering-montaison stage and maturity or ripe grain stage). A total of 1258 larvae were collected, i.e. 506 larvae in 2021 and 752 in 2022, spread over three regions and nine sites.

Tracking caterpillars in the laboratory

Rearing was set up in the entomology laboratory of ISRA/CDH at an ambient temperature of 24-26°C. Petri dishes measuring 90mm x 14.2mm containing fresh food, mainly corn leaves, were replaced every 48 hours throughout the laboratory phase. The duration of the development cycle of *S. frugiperda* was determined after each collection. The sampled larvae are returned to the entomology laboratory, isolated and fed to pupation. The resulting nymphs are isolated individually in boxes and followed until the emergence of an adult of *S. frugiperda*, parasitoid or entomopathogenic nematode. After the emergence of adults of *S. frugiperda*, mating was carried out between males and females, the eggs laid were monitored daily to know the date of hatching. Neonates were also followed up to pupation to determine the duration of the larval phase. Also, the duration of the nymphal phase was determined by daily pupal monitoring until adult emergence. The lifespan of adults was assessed by following newly emerged adults until death. In the case of emergence of natural enemies, individuals are counted and classified according to their status (parasitoids, entomopathogens nematodes) using a dinolite microscope synchronized with a computer through a Dinocapture 2.0 link application version 1.5.43 and an the entomological identification key (Delvare & Aberlenc, 1989) [10]. No dissection was done to examine larvae where there was no emergence of parasitoids. Some parameters have been studied including abundance, frequencies. Frequency (f) is defined as the percentage of individuals of a species according to the total number of individuals in the sample.

Frequency of occurrence (FO), defined as the percentage ratio between the number of surveys or removals where a species (i) was noted and the total number of all surveys multiplied by 100. In this study, the total number of observations or surveys was 4. Relative abundance is the ratio of the number of individuals of a given species per unit area to the total number of individuals of all species combined.

$$\text{FO (\%)} = \frac{\boldsymbol{Pi}}{\boldsymbol{P}} *100$$

Pi= number of surveys with species i, P=total number of surveys

FO values are classified into different groups:

- Constant species are present in more than 50% of surveys;
- Accessory species are present in 25% to 50% of surveys;
- Accidental species are present in less than 25% of surveys

The parasitism rates of each natural enemy were also determined from the number of parasitized larvae divided by the total number of larvae collected, all multiplied by one hundred as described through the formula below :

$$\text{\% of parasitism} = \frac{\text{Number of parasitized larvae}}{\text{Total number of larvae collected}} \mathbf{*100}$$

Data analysis

All the tracking data of the caterpillar's natural enemies were recorded and arranged under an Excel spreadsheet. The exploitation of data is done and tests of normality, comparison of averages are carried out in the R Studio version 4.2.2 and xlstat software to see in particular the differences in significance between production areas. The means were discriminated according to the normality of the data on the basis of a linear model of analysis of variances (ANOVA) using the test of Tukey HSD, Kruskal wallis at the threshold of α equal 5% and the test of Man Whitney.

Results

Development stages of *S. frugiperda* at ambient temperature (25±1°C)

At room temperature (25-26°C) in the laboratory, life cycle of S. *frugiperda* is between 25 and 30 days. Egg incubation can take 3±1 days when the temperature is 28-30°C. The duration of development of the larval stage is between 15 and 18 days (16 on average). The duration of the nymphal stage is 8 days±1. Life duration of adults is around 15 days. The duration of the armyworm development cycle is on average 27 days.

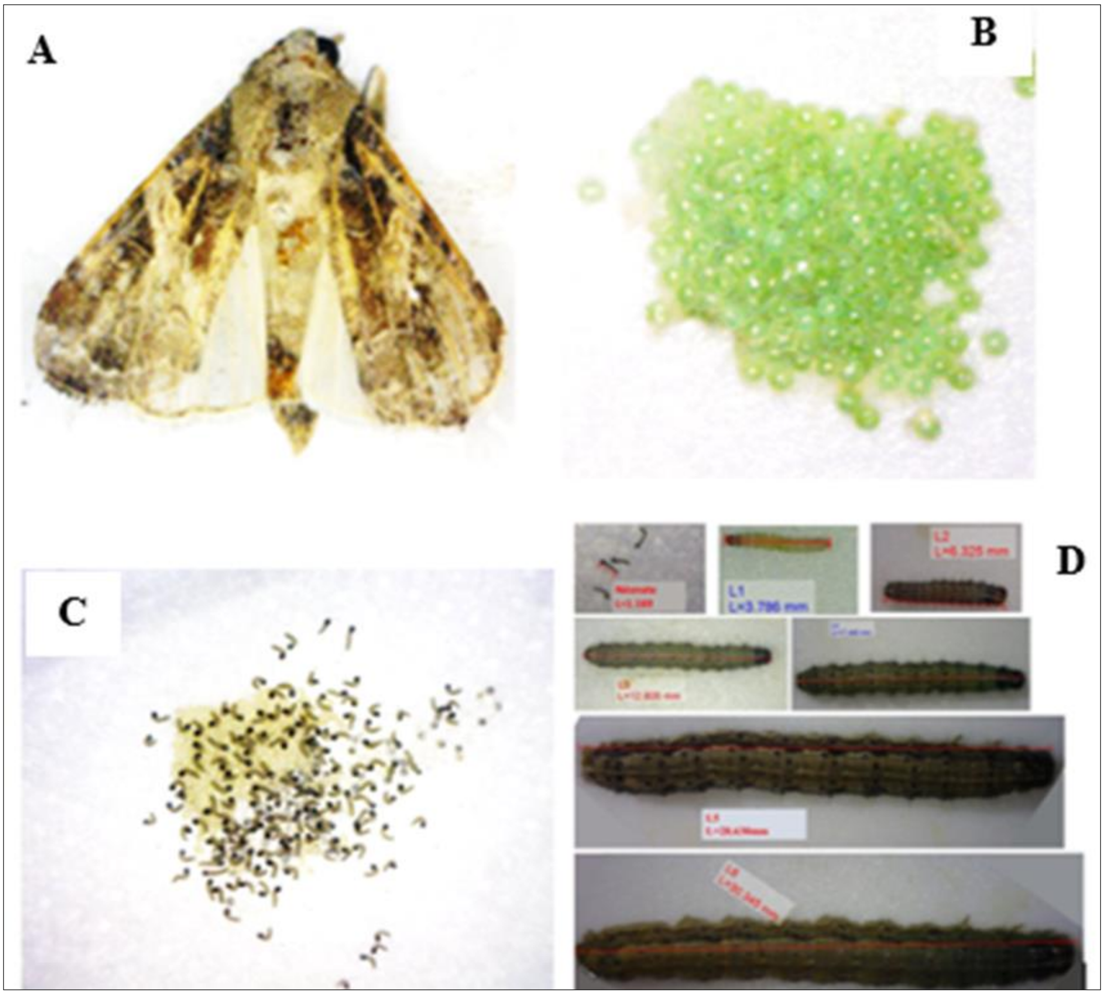

Fig 2: Development stages of S. *frugiperda;* (A) Adults of S. *frugiperda,* (B) Eggs of S. *frugiperda,* (C) Neonate larvae of S. fruigiperda, (D) Development stage of S. *frugiperda* larvae

Parasitoids emerging in the laboratory

The table below shows the parasitoids that emerged in the laboratory according to family. A total of 159 individuals belonging to two orders (Hymenoptera and Diptera) divided into eight families (Ichneumonidae, Braconidae, Evanidae, Tachinidae, Syrphidae, Scoilidae, Sphecidae and one unidentified family) have been recorded over the last two years. Parasitoids of the Tachinidae family are the most represented, with a percentage of 77.98%. The Kaffrine and Tambacounda regions have a high biodiversity of parasitoids, compared with the Kaolack region, where biological control was only observed with Diptera (75 individuals).

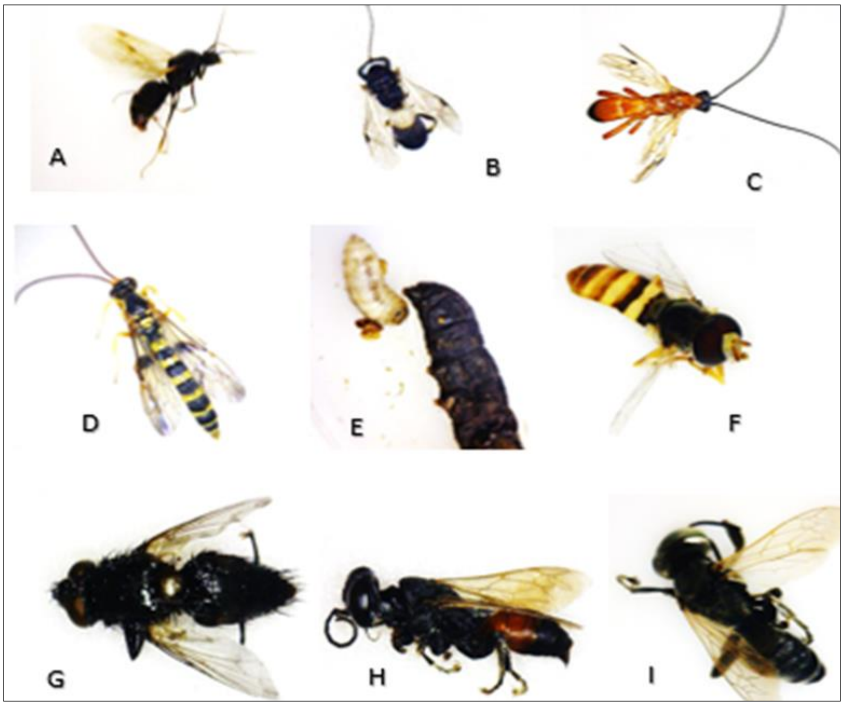

Fig 2: *Parasitoids emerged from FAW juvenile stages. Hymenoptera :* (A) *Scoilidae,* (C) *Braconidae,* (D) *Ichneumonidae, (E) Larval Ichneumonidae, (H) family unidentified; Diptera:* (B) NI*= *unidentified family,* (F) *Syrphidae*, (G) *Tachinidae*, (I) *Tachinidae*

Table 3: Distribution of natural enemies found in the laboratory by site

Region	Sites	Orders	Famillies	Number of individual
Tambacounda	*Ngolol-keba*	*Hymenoptera*	*Ichneumonidae*	3
			Braconidae	6
			Evanidae	2
		Diptera	*Tachindae*	2
	Dane-niako	*Hymenoptera*	*Icheumonidae*	3
	Sare-Sambourou	*Diptera*	*Tachinidae*	2
		Hymenoptera	*Braconidae*	9
Kaolack	*Mbiteyene*	*Diptera*	*Tachinidae*	49
	Keur Ousmane			9
	Keur Abibou Niass			17
Kaffrine	*Ndjigui*	*Diptera*	*Tachinidae*	45
			Syrphidae	3
		Hymenoptera	*Scoilidae*	2
	Ndiognick	*Hymenoptera*	*Braconidae*	1
	Taïf	*Diptera*	*Syrphidae*	1
		Hymenoptera	*Braconidae*	2
			Sphecidae	1
			Scoilidae	1
			*NI**	1
Total	9	2	8	159

Frequency of parasitoid species found

Biodiversity is a synthetic concept that combines individual abundance, species frequency and species richness. The results for species frequency are shown in the graph below. In the Kaolack region, all the species recorded belong to the Tachinidae family (100%.). In Tambacounda, only four insect families were recorded, the most frequent being Braconidae, Ichneumonidae and Evanidae (10.52%), followed by Tachinidae (5.26%). In Kaffrine, six insect families were recorded, Syrphydae, Scoilidae and Braconidae (10.52%) were the most frequent. Although Tachinidae are less represented in Kaffrine and Tambacounda (5.26%), they are the most frequent family of all, as they were recorded in all study areas.

Fig 2: Frequency of parasitoid species found

Frequency of occurrence of parasitoid families

It was calculated for all the families found and the results are shown in the graph below. Analysis of the graph reveals that the Tachinidae family has a maximum frequency of occurrence of 100%, making it a ubiquitous or constant species at Kaolack, followed by the Braconidae at 50%, the Ichneumonidae at 33.33% (accessory species) and families with a frequency of occurrence of less than 25%, i.e. accidental species.

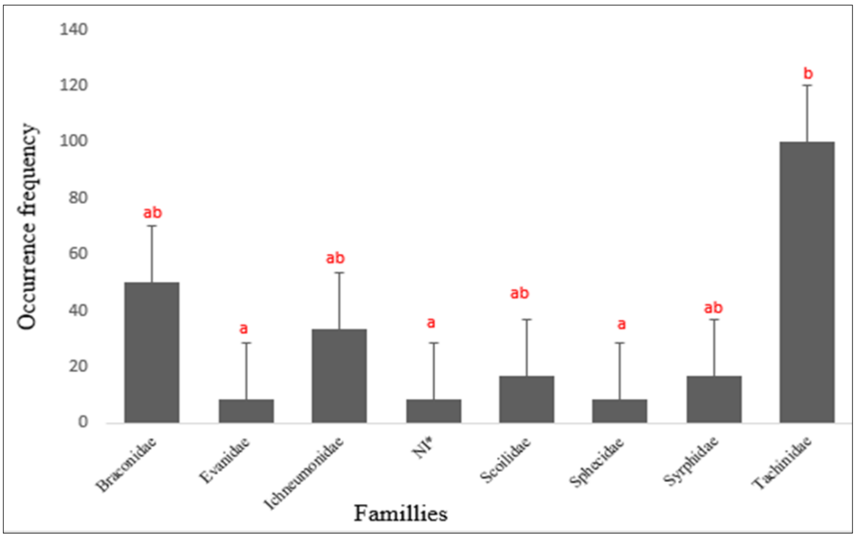

Fig 3: Frequency of occurrence of families found

Relative abundance of parasitoids

The results below summarize the relative abundance of the insect families inventoried during this study. They are represented in a treemap diagram and also indicate the quantity or number associated with each insect family. Each family is represented by a rectangle, the size of which indicates the corresponding quantity. In the case of this study, in the Kaolack region, the relative abundance of Tachinidae is 100%, i.e. all 75 individuals encountered belong to the order Diptera and the family Tachinidae. In the Kaffrine region, of the 57 species recorded, 78.94% belong to the family Tachinidae, 7.01% to the family Syrphidae, 5.26% to the families Braconidae and Scoilidae and 1.75% to the family Sphecidae and unidentified. Unlike in the Kaffrine region, in Tambacounda, of the 27 species classified, 55.55% belong to the Braconidae family, 22.22% to the Ichneumonidae, 14.81% to the Tachinidae and 7.40% to the Evanidae family. Overall, Tachinidae are more abundant, followed by Barconidae, Ichneumonidae, Evanidae, Syrphidae, Scoilidae and Sphecidae and unidentified.

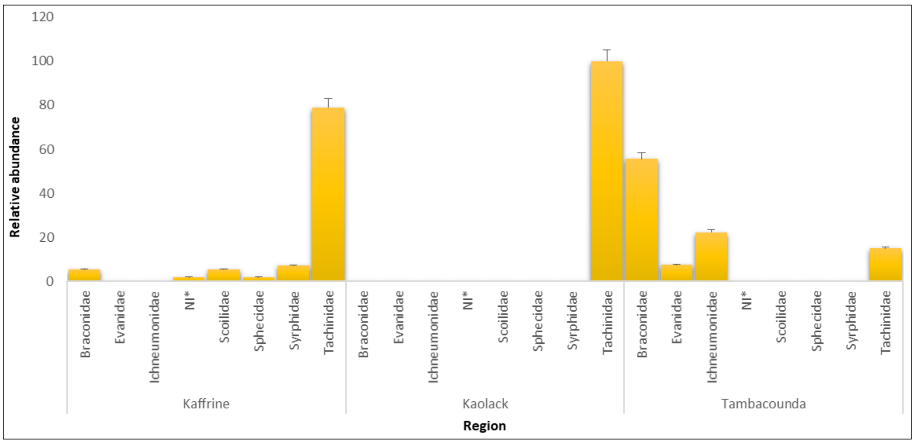

Fig 4: Relative abundance of insect families

Percentage of parasitism by site

The table below (Table 3) summarizes the total number of larvae collected and parasitism levels according to study sites and regions. A total of 1258 caterpillars were collected in the three regions: 595 in Kaffrine, 397 in Kaolack and 266 in Tambacounda. Of the 1258 larvae collected, 429 were parasitized by entomopathogens (nematodes) and 94 by parasitoids, giving a total of 523 parasitized larvae. Nematode parasitism was noted at all study sites, with average incidence ranging from 10 to 32%. The Kaolack region is the most affected by nematodes, with percentages of parasitism ranging from 27 to 32%, followed by the Kaffrine region (14 to 24%) and the Tambacounda region (10 to 22%). The incidence of parasitoids varies from 0.43 to 21%, depending on the site. Parasitoid parasitism was highest in the Tambacounda and Kaolack regions, at around 12%, it is lower in the Kaffrine region (7.39% on average).

Table 4: Parasitism levels according to study sites

Regions	sites	Total number of larvae collected	Number of larvae parasitized by nematodes	Number of larvae parasitized by parasitoids	% parasitism of nematodes	% parasitism of parasitoids
Kaolack	Mbiteyene	117	67	16	29.5336	7.9126
	Keur abibou	144	63	13	32.2178	12.7102
	Keur ousmane	136	62	4	27.1701	13.2650
Kaffrine	Ndjigui	236	57	26	14.8553	21.4742
	Ndiognick	159	51	1	24.7935	0.2717
	Taif	200	63	3	21.1130	0.4360
Tambacounda	Dane-niako	86	27	8	22.5369	11.1507
	Ngolol-keba	135	26	13	10.6026	17.0448
	Sare-sambourou	45	13	10	21.0213	7.7067

Parasitoid parasitism levels by region

The graph below (figure 6) shows the level of parasitism caused by parasitoids according to the study regions. Statistical tests show non-significant levels of parasitism (p-value ≥ 0.05). The levels of parasitism observed were practically low for all three regions, ranging from 7.39 to 11.96 on average. However, parasitism levels observed in the Tambacounda and Kaolack regions are not negligible, reaching around 12%.

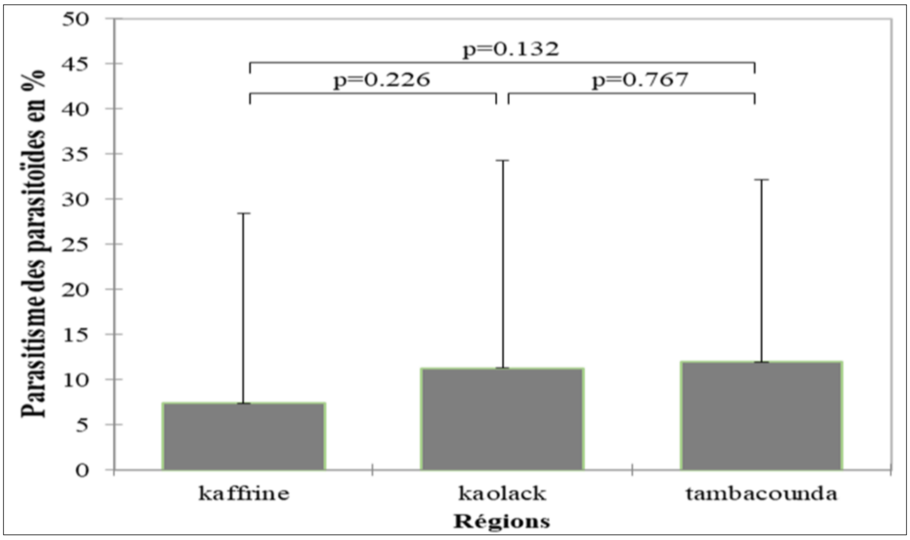

Fig 6: Parasitism of parasitoids according to region

Nematode parasitism levels by region

The graph below (figure 5) shows the percentage of larval samples parasitized by nematodes according to study region. Statistical tests show non-significant levels of parasitism between regions (p-value ≥ 0.05). The lowest levels of parasitism were observed in the regions of Kaffrine (20.2472%) and Tambacounda (18.0536%). The Kaolack region recorded the highest level of parasitism, averaging almost 30%.

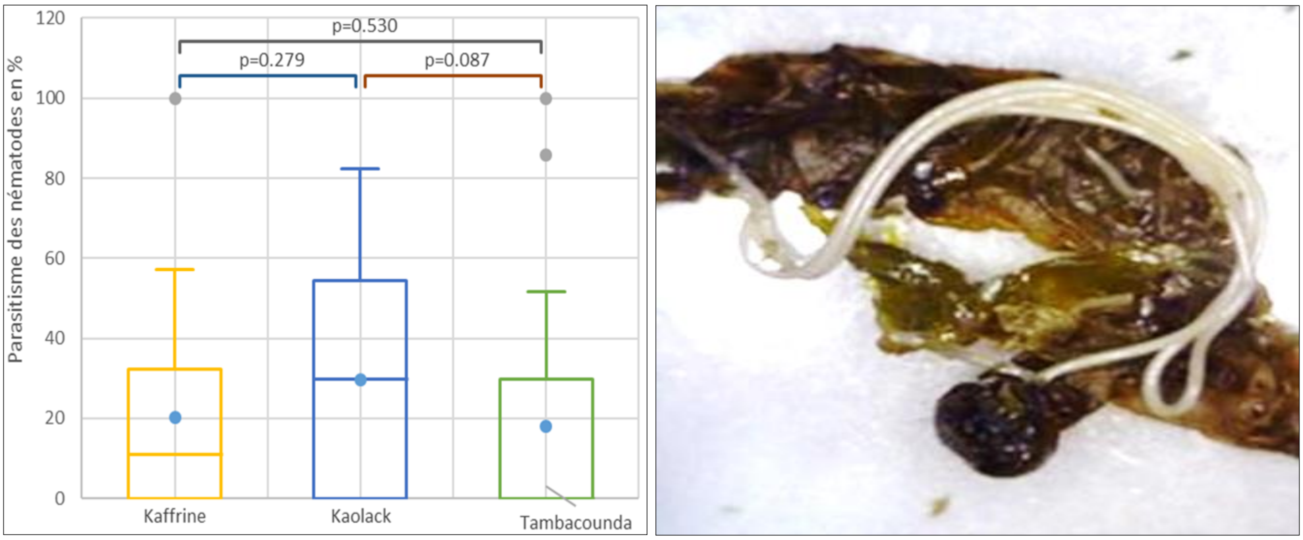

Fig 2: Parasitism of nematodes according to regions

Discussion

Several control strategies have been adopted to manage *S. frugiperda* populations. These control alternatives concern chemical control, genetic control through the use of genetically modified plants (Bernardi *et al.*, 2014) [4] physical or mechanical control, agronomic control through push-pull and biological control through the use of organic extracts and living organisms, excluding's utilisation of non living extraits (Scapinello *et al.*, 2014; Sosa *et al.*, 2017) [44]. However, some studies, including that of Bernardi *et al.* (2017) [3, 37] reveal that these control methods have limitations due to the resistance developed by *S. frugiperda*. Biological control, which is "the use of living organisms to suppress the population density or impact of a specific pest, appears to be a serious alternative for managing this pest. In nature, the population of each organism is regulated and maintained in fluctuation between the highest and lowest thresholds, often below economic damage thresholds. These fluctuations are often due to biotic regulatory actions such as food availability, parasitism (pathogens and parasitoids), predation, or by abiotic factors such as climate and soil (Prasanna *et al.*, 2018). Such population regulation is called natural control. It therefore becomes necessary to know the various natural enemies able to keep the armyworm at low nuisance thresholds. The aim of the present study was to contribute to the inventory and identification of the natural enemies of *S. frugiperda* in maize crops and in the study areas. Natural enemies are recognized in agroecosystems for their role in the natural regulation of phytophagous insects. They promote a balance in arthropod communities, helping to reduce dependence on pesticides. To this end, caterpillar monitoring work was carried out in the laboratory during these two years (2021 and 2022), and showed that the development cycle of the armyworm caterpillar takes around 25 to 30 days (27 days on average) at room temperature (25°C). These results are similar to those of Prasanna *et al.* (2018) who state that the development cycle is around 30 days (daily temperature ~28°C) during the hot summer months. However, our results do not corroborate those of Tendeng *et al.* (2019) [46] who obtained a cycle between 22 and 28 days with an average of 25 days at 25°C. (Castro & Pitre, 1988) [7] Stipulate that when caterpillars are fed maize leaves, the development cycle is 35 to 45 days. The length of the cycle may vary depending on the host plant and weather conditions, but the more favorable the weather conditions (at 28 to 30°C), the shorter the development cycle. Jeger *et al.* (2017) [19] state that the caterpillar is a formidable invasive pest because it has a fairly rapid development cycle that varies with temperature. The optimum temperature for larval development of *S. frugiperda* is 28°C, but it can be lower for oviposition and pupation. Dumas *et al.* (2015) [12] also show that the pest has a preference for Poaceae, particularly maize.

The parasitoids found represent species of Hymenoptera (Ichneumonidae, Braconidae, Evanidae, Sphecidae, Scoilidae, and one unidentified) and Diptera (Tachinidae, Syrphidae). These results are similar to those of (Molina-Ochoa *et al.*, 2003b) who made an inventory of 150 species of parasitoids of *S. frugiperda* larvae in the Americas and the Caribbean, belonging to the families Braconidae (Aleoides, Chelonus, Cotesia, Glyptapanteles, Homolobus, and Meteorus genera), Ichneumonidae (Campoletis, Eiphosoma, Ophion, and Pristomerus). They are in line with our collection, which reports a total of 159 species recorded at the nine study sites. Sisay *et al.* (2018) [43] in the same logic of reporting the natural enemies of armyworms in three East African countries, recorded five parasitoid species belonging to the Braconidae (Cotesia icipe, Coccygidium luteum, Chelonus curvimaculatus Cameron), Ichneumonidae (Charops ater Szépligeti) and Tachinidae (Palexorista zonata). Indeed, they also suggest the existence of a wide diversity of parasitoid species for this pest. For example, in North and South America, the region of origin of the pest *S. frugiperda*, studies carried out in various countries have documented several species of natural enemies, such as Hymenoptera and Diptera in Mexico and in the highlands of Honduras (Molina-Ochoa *et al.*, 2004; RuizNájera *et al.*, 2013; Sisay *et al.*, 2018) [43]. In addition, other studies carried out in the Kaolack and Kaffrine regions (Ndiaye *et al.*, 2021) listed a wide range of natural enemy species belonging to the same families. This diversity of parasitoid species is mainly responsible of the pest mortality of the pest. In the case of this study, the sites in the Tambacounda and Kaffrine regions were surrounded by millet, peanut, cotton or cowpea production, unlike the Kaolack region, where all the sites surveyed were adjacent to maize monoculture plots. As a general rule, Seghieri & Harmand, (2019) [38] assert that plant biodiversity indirectly influences pest populations by promoting the development of natural enemies, at plot or landscape level. And, increasing landscape complexity very often results in an increase in the diversity and abundance of natural enemies including predators and parasitoids (Rusch *et al.*, 2016; Shackelford *et al.*, 2013) [39]. This landscape complexity also acts on crop colonization through its structure, which can limit or facilitate the movement of organisms between different patches depending on their dispersal capacity Hassan, (2012) [17]. However, of all the species found, Tachinidae are the most frequent and are represented in all the study areas, followed by Braconidae in Tambacounda and Kaffrine. The frequency of Tachinidae diptera in these regions can be explained by the high infestation rates observed in the Kaolack and Kaffrine regions. In fact, Diptera often have very different lifestyles, with larvae and adults being very different. This duality has enabled these insects to populate all environments, as the female's behavior generally establishes the link between the two lifestyles. They are most often found in both tropical and temperate climates, and in a wide variety of rural and urban environments. Also, their distribution is affected by various factors including reaction to light, temperature, humidity, color and surface texture (Sankara, 2017). In addition, the existence of a large basin in the heart of the old basin in the Kaolack region, which is flooded every year, could lead to an increase in entomofauna, particularly Diptera. In addition, the survey carried out at the start of the study focused on different farming practices, such as planting dates, use of compost and manure, armyworm caterpillar management methods, crop rotation from one site to another, and plant heterogeneity, which could explain the diversity of species observed between the study areas. Differences in parasitoid species abundance may be largely due to environmental differences, in addition to climate, adjacent crops and alternate hosts. Several factors affect the abundance of natural enemies, including sample size, plant diversity, the level of adaptation of natural enemies, and the growth and density of *S. frugiperda* populations. In addition, the vegetative development of maize plants increases the abundance of armyworms, which in turn may be responsible for the increase in natural enemies and the diversity of species found in production plots. Also, Wyckhuys & O'Neil, (2006) [50] studied the relationship between armyworm population dynamics and associated natural enemies in maize fields in the highlands of Honduras. They conclude that: the more abundant *S. frugiperda* populations are, the greater the possibility of finding natural enemies. This corroborates our results, which conclude that the majority of natural enemies were found in the Kaolack and Kaffrine regions, where 78.85% of collections were made. Other studies (Laminou *et al.*, 2022; Prasanna *et al.*, 2018) [21] have shown that the fall armyworm is sensitive to the sowing period, the cropping system, deep tillage to unearth the chrysalises and expose them to bad weather. They also stated that weed control could affect the abundance of *S. frugiperda* populations, as certain weeds such as Agrotis spp, Digitaria spp, Sorghum halepense and Cenchrus tribuloides harbor the pest. Our results are in line with those of Channakeshava & Somanagouda, (2020) [8] who assert that the increase in the pest causes an increase in the number of natural enemies through a dependent population phenomenon. Ruíz-NáRuíz-Nájera *et al.* (2007) in their work entitled "Survey of Hymenopteran and Dipteran parasitoids of the fall armyworm (*Lepidoptera*: Noctuidae) in Chiapas, Mexico", they explain that variation in species presence and parasitism levels may be due to differences in geographical location, agronomic practices, crop type and development stage.

A study by Omoto *et al.* (2016) shows that crop rotation can affect *S. frugiperda* populations in production fields and thus natural enemies. All these parameters and other studies justifying the diversity and abundance of parasitoid insects recorded in the different study regions explain the level of parasitism observed in the Kaolack. Of the 1258 *S. frugiperda* larvae collected in the different regions and monitored in the laboratory, 523 larvae were found to be attacked by natural enemies, including entomopathogenic nematodes and parasitoids. 429 of the larvae collected were parasitized by nematodes, i.e. an incidence of 34%, and 94 by parasitoid insects, i.e. 7.47%. Overall, a parasitism rate of 41.57% was noted, distributed among nematodes of the genus Hexamermis according to studies by (Firake & Behere, 2020; Tendeng *et al.*, 2019) [13, 46] Hymenoptera and Diptera. The parasitism rate is equal to the mortality rate, as all larvae collected that had undergone parasitism by either endoparasitic nematodes or insect parasitoids were found dead. These parasitoids and endoparasitic nematodes could thus contribute to the natural regulation of *S. frugiperda* populations.

Conclusion

The present study was carried out as part of the program to manage the armyworm through integrated management strategies (IPM) to reduce the socio-economic impact of the pest (KAFACI-FAW). The aim was to determine and identify the natural enemies of *S. frugiperda* in a number of maize-growing areas in Senegal. The results obtained confirm new associations of natural enemy species with the armyworm in West Africa, particularly in Senegal. Several parasitoid species were identified, totalling 159 individuals in two orders and eight families, one of which is unidentified. The Tachinidae diptera were the most represented with nearly 78% of the total natural enemy population, followed by the Braconidae and Ichneumonidae hymenopterans with 11.32% and 3.77% respectively. The rate of parasitism by nematodes and parasitoids was highest in the Kaolack and Tambacounda regions respectively. Information on the incidence of parasitoids and parasitism rates of natural enemies is of paramount importance for the design of a biological control program against armyworm, whether through conservation of native natural enemies or additional releases. It is therefore important to protect natural enemies from the harmful effects of plant protection products, and to devise more comprehensive IPM strategies for managing armyworm in these agroecological zone.

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