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Annual dynamics of fall armyworm populations in West Africa and biology in different host plants

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ABSTRACT

Since its recent introduction in West Africa, the fall armyworm *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) has severely damaged maize and other crops. Control efforts face many challenges as the knowledge on this invasive pest is still limited. In this study, we assessed the annual population dynamics by monitoring this species using pheromone traps and visual observations, so as to contribute to the development of an integrated management strategy. In addition, we also evaluated some life history traits of *S. frugiperda* on different local host plants to identify the most suitable hosts in Burkina Faso.

Adult captures were recorded throughout the year, as a result of a favorable mean annual temperature (29°C). Two population peaks occured: one peak (15.5±3.1 adults per trap and per month) was recorded in December and January (dry season) while the second peak (17.5±2.5) occured in July and August (rainy season). These peaks were synchronized with the major maize production periods of the region, usually 1 to 2 months after planting, when the plants had 6 to 12 leaves. In addition, the proportion of infested maize fields and infested plants per field was higher in the dry season (94.0% and 44.9%) than in the rainy season (80.0% and 26.2%). Based on the larva to adult survival rate (65-80%), mean fecundity (700-1000 eggs per female) and short life span of 36-38 days, pearl millet, maize and groundnut were found the most suitable hosts for the insect development.

To better manage this insect pest, we suggest monitoring efforts in all crops associated with maize, the use of short-cycle varieties and early planting. In addition, curative treatments are more effective when applied on young maize plants, as the early instars are the most susceptible.

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Introduction

The fall armyworm *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) was detected in 2016 in Nigeria [1] and subsequently in several other countries including Burkina Faso [2]. Although it has a preference for maize, the fall armyworm also causes significant losses on many commercial crops such as groundnut, soybean, rice, sorghum, sugarcane and cabbage [1,3]. Estimated yield losses in maize crops ranged from 22-67% in Ghana and Zambia [3] and from 12-58% in Zimbabwe [4]. As a result, the food and nutritional security of millions of producers is threatened.

The fall armyworm is a highly mobile and polyphagous pest [1,5]. Many generations of this pest occur in a year because it does not undergo diapause. Moreover, its cycle is relatively short (25 - 30 days) at an average daily temperature of 25 °C [6,7]. Damages are caused by larvae that attack maize plants at their growing points and bore into the maize cob to feed on the kernels [8,7]. Over the year, the dynamics and abundance of insect populations are influenced by the availability of host plants and environmental conditions (relative humidity, temperature, rainfall) [9,6]. The cycle is interrupted in regions characterized by a severe winter between crops, reducing population abundance [10]. Overwintering fall armyworm populations in South Florida are responsible for annual infestations that spread to central and eastern United States and southern Canada [8].

The management strategies applied in Africa (including synthetic pesticides and sometimes alternatives) are mainly based on the data available from the America [11,12]. However, Africa is likely to experience the greatest increase in fall armyworm threats according to predictive models based on the pest distribution patterns, land use and topography [13]. Therefore, several works are carried out to identify effective chemical and biological insecticides [14], but also alternatives such as cultural methods and biological control [15,11]. In Burkina Faso, where average annual temperatures and crop diversity are favorable to the development of the fall armyworm, this pest was expected to persist throughout the year. In the maize production regions (Hauts-Bassins region), maize is produced twice a year, during the rainy and the dry seasons [16,17].

Developing an effective integrated management strategy against the fall armyworm requires basic information such as its population dynamics. A study conducted in Ghana reported that environmental factors such as rainfall, temperature and relative humidity influence the abundance of the pest [18]. In West Africa, and in Burkina Faso in particular, knowledge on the fall armyworm seasonal dynamics is very limited. Among the consequences, chemical treatments are performed preventively at any period of the year [14]. In this study, we assessed the annual population dynamics by monitoring this species using pheromone traps and visual observations, so as to contribute to the development of an integrated management strategy. In addition, we also evaluated some life history traits of *S. frugiperda* on different local host plants to identify the most suitable hosts in Burkina Faso.

Materials and methods

Seasonal dynamics of fall armyworm

Moth trapping was performed in three maize production sites in the province of Houet from January to December 2020. The province of Houet is located in the Hauts-Bassins region, which belongs to the Sudanian zone, and experience an average annual rainfall of 900 to 1200 mm [19,17]. The region is characterized by a dry season from November to May and a rainy season from June to October.

Fall armyworm abundance was recorded using white delta traps and commercial pheromone lures for fall armyworm provided by Pherobank BV (The Netherlands). Delta traps consist of a triangular shaped body made of opaque white plastic, and a removable insert covered with a thin coating of high-quality, non-drying glue placed inside on the floor of the triangle. Male moths and other insects entering through the vents on both sides are captured by the glue on which the lure is placed. Four traps were installed at each of the three sites located in Bama, Léguéma and Nasso (Fig. 1). Each trap was suspended at a height of 1.5 m from the ground; and the traps were approximately 200 m apart at each site. In Bama, the traps were installed in an irrigated perimeter where maize, rice, sweet potato, cassava, cowpea, and groundnut are produced throughout the year. Production in Léguéma was dominated by vegetables (tomato, cabbage, common bean), cowpea and maize. In Nasso, maize, groundnut and rice were produced throughout the year. The sites were about 40 km apart. The traps were emptied every two weeks to count the males captured and the insert renewed. The pheromone dispenser was renewed every month.

To assess the infestation rate, randomly selected maize fields (n=107) were also surveyed for the presence of fall armyworm eggs and larvae during the dry (54 fields) and rainy (53 fields) seasons. Every two weeks, we visited four maize fields (different field on every visits). In each field, 25 plants were selected by using a "W" pattern, and sparing border plants [7]. A distance of 5 meters separated each observation point, where 5 maize plants were inspected. Data on mean monthly temperature and precipitation for the study period were obtained from the Infoclimat weather archive [20].

Biology of fall armyworm on different hosts

An assay was conducted to evaluate the developmental capacity of the fall armyworm on ten common crops: maize; *Zea mays* L. (v. FBC 6), pearl millet; *Penissetum glaucum* L. R. Br. (v. Missari), sorghum; *Sorghum bicolor* L. (v. Kapelga), groundnut; *Arachis hypogea* L. (v. Fleur 11), cowpea; *Vigna unguiculata* L. Walp. (v. Komkallé), rice; *Orizea sativa* L. (v. Nerica 4), onion;

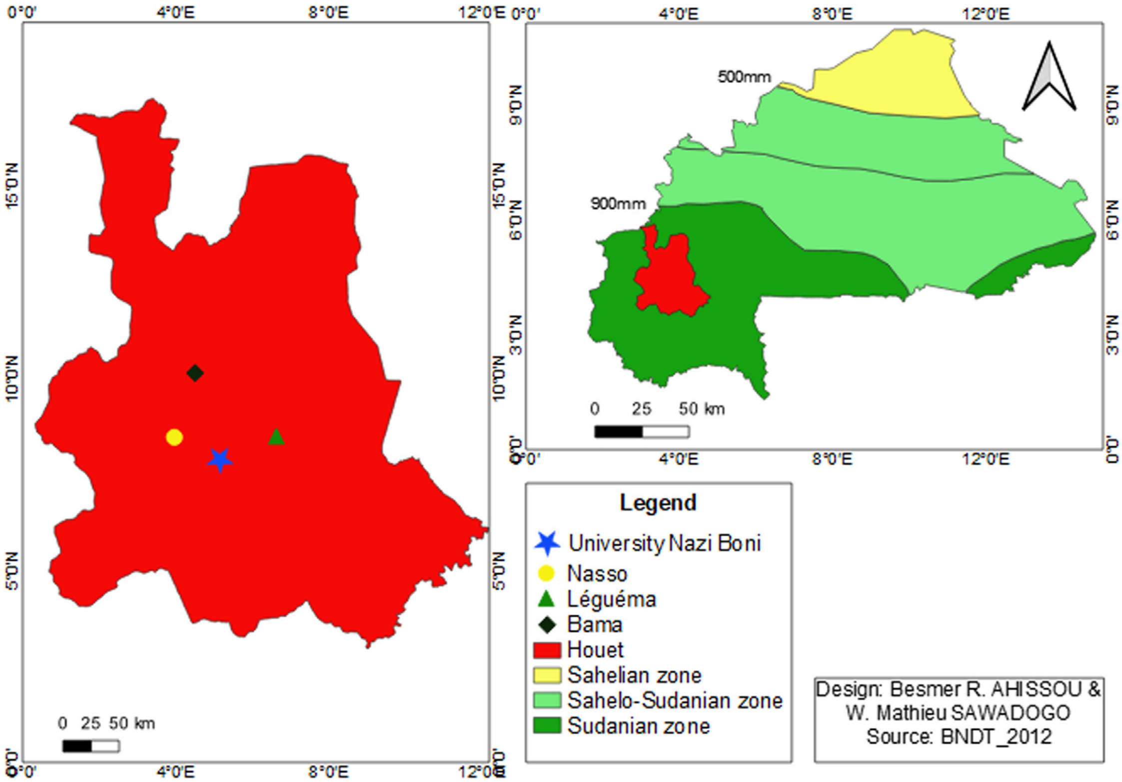

Fig. 1. Insect capture sites, located in the province of Houet (red zone) where fall armyworm traps were deployed over the year (left figure). Climatic zones in Burkina Faso (right).

Allium cepa L. (v. Noflaye), okra; *Abelmoschus esculentus* L. Moench (v. Indiana), cotton; *Gossypium hirsutum* L. (v. FK64) and tomato; *Solanum lycopersicum* L. (v. Mongal F1). These plants were grown in 15 liters pots filled with soil, and placed in a greenhouse belonging to the Training and Research Centre of the University Nazi Boni (UNB) in Bobo Dioulasso, Burkina Faso. Leaves of 1 - 2 months old plants were used for the test.

Fourth and fifth instars, as well as egg masses, were collected from the field and maintained under laboratory-controlled conditions (25±2°C, 60±15 % relative humidity and 12:12 photoperiod) and fed on fresh maize leaves for seven generations [21]. Eggs laid in a single layer on white paper were used to facilitate separation with a fine brush. Forty individual eggs were placed on four fresh leaves of each crop plant (for a total of 160 eggs per crops). The newly hatched larvae were fed individually in 300ml plastic boxes with fresh leaves of one of the selected crops. Insect development and survival were checked twice a day (8 am and 4 pm). Pupae were collected daily and placed in a cage (60 × 40 × 40cm). The bottom of the cage was covered with white paper for female oviposition. Emerged adults were fed a sugar water solution (100 g/l) throughout their lives. The white paper was removed after oviposition, and cut to individualize each egg mass into separate boxes. Trials were performed under controlled laboratory conditions (26±2°C, 70±15 % relative humidity, and photoperiod 12L:12D).

Data analysis

Data of larval, pupal and adult period duration were analyzed for normality by the Shapiro-Wilk test and and homoscedasticity by Levene test and were expressed as mean ± standard deviation. They were analyzed using the Kruskal-Wallis test and followed by the pairwise comparisons with the 'pairwise.wilcox.test' function. Due to the complete separation of catch data from different sites and the variable presence probability on each site, they were analyzed using zero-inflated regression models to determine the influence of climate variables (annual temperature and precipitation) on fall armyworm catch with the 'glmmTMB' function in the 'glmmTMB' package for R. The survival data (larvae to lupae and larvae to adults) and fecundity (number of eggs laid per female) were fitted in a generalised linear models (GLMs) analysis, binomial and Poisson family respectively. Multiple comparisons for survival and fecundity data were performed with Tukey's post-hoc test using the 'ghlt' function in the 'multcomp' package for R. Finally, the 'prcomp' function was used to perform Principal Component Analysis (PCA) and Biplot is generated by using the 'fviz_pca_biplot' function in the 'factoextra' package for R. In the Biplot, the lines represent the measured variables and the points represent the evaluated crops. All analyses were performed in R statistical software [22] using the RStudio-2021.09.2 interface.

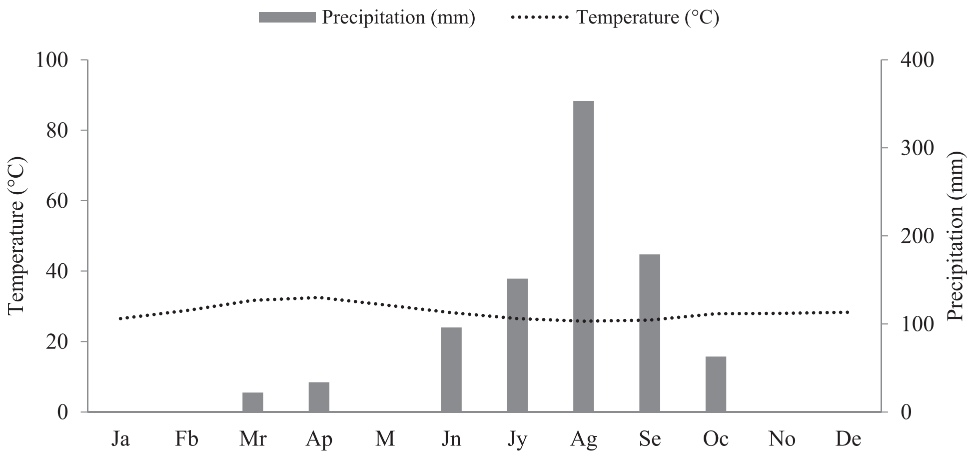

Fig. 2. Monthly average temperature and precipitation data during the study period.

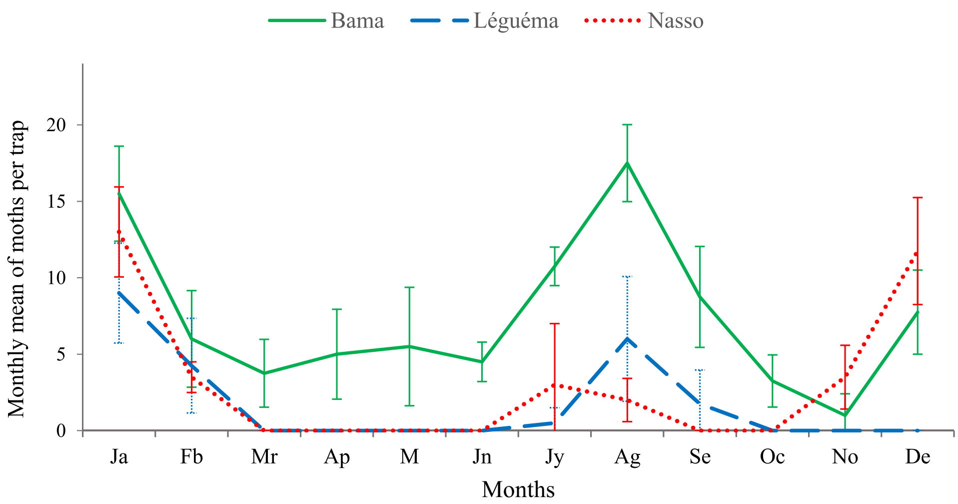

Fig. 3. Monthly mean number of fall armyworm catches per trap during one year of sampling in three maize production areas. Data are means ± standard deviation.

Results

Annual temperature and rainfall

During 2020, the annual temperature ranged from 19.9 to 38.5°C. The region is characterized by a dry season (November - May) and a rainy season for the rest of the year, for a mean annual rainfall of 898mm (Fig. 2).

Infestation

Fall armyworm adults were captured throughout the year. In the three sites, the adult catches showed two peaks. The first peak was recorded in December and January (dry season) and the second in July and August (rainy season). In contrast, low densities were recorded between March and June. At the site where the highest number of adults was recorded (Bama), the monthly average number per trap was 15.5 ± 3.1 (1st peak) and 17.5 ± 2.5 (2nd peak) (Fig. 3). The zero-inflated regression models revealed that there is significant difference in moth presence between months at different sites (P-value < 0.0001). In addition, when moths were present, captures were significantly negatively correlated with temperature (P-value < 0.0001) and rainfall (P-value $= 0.008$).

The proportion of *S. frugiperda* infested maize field reached 80% in the rainy season and 94% in the dry season. However, the percentage of infested plants per field in the rainy season (26.2%) was lower than in the dry season (44.9%).

Table 1
Mean duration ± standard deviation (days) of larvae, pupae, and adults of the fall armyworm fed on different crops under controlled conditions. For a given column, different letters indicate significant differences among crops according to the Kruskal-Wallis test followed by Pairwise Wilcox Test.

Crops	Developmental time		Adult lifespan
	Larvae	Pupae	
Maize	15.1±0.7 d	8.8±1.0 b	10.1±1.3 abcd
Pearl millet	14.7±0.9 d	8.9±0.8 b	10.3±1.2 abcd
Cowpea	20.2±1.2 a	8.8±0.7 b	9.0±1.4 d
Sorghum	18.8±1.4 b	9.7±1.1 b	9.6±1.6 abd
Okra	24.3±4.1 e	9.5±1.4 b	14.0±4.4 e
Groundnut	16.8±1.3 c	8.8±0.8 b	9.5±1.4 ad
Rice	20.2±2.8 ab	9.5±1.1 b	11.8±2.1 bce
Tomato	30.1±3.1 f	8.8±0.5 b	11.2±0.9 c
Onion	19.0±1.9 b	9.5±0.8 b	9.2±1.3 d
Cotton	20.1±1.5 ab	10.9±0.9 a	10.7±0.9 abc
P-value	< 0.0001	< 0.0001	< 0.0001

Table 2
Survival rate and fecundity of the fall armyworm fed on different crops under controlled conditions. For a given column, different letters indicate significant differences among crops (GLM, Binomial family for survival rate and Poisson family for fecundity; Tukey test, $p < 0.05$). n.a. refers to non-applicable. Data are means ± standard deviations.

Crops	Survival rate (%)		Fecundity (eggs/female)
	Larvae to Pupae	Larvae to Adults	
Maize	72.5±10.2 de	72.5±10.2 cd	1009.8±73 f
Pearl millet	67.5±17.2 ce	65.0±19.7 bd	727.6±160 e
Cowpea	67.5±14.7 ce	62.5±12.2 bc	527.5±123 b
Sorghum	62.5±15.0 cd	57.5±12.6 bc	646.4±136 d
Okra	82.5±14.6 e	72.5±3.5 cd	454.8±48 a
Groundnut	80.0±6.1 e	80.0±6.1 d	1000.4±161 f
Rice	55.0±10.2 c	55.0±10.2 b	596.8±66 c
Tomato	20.0±8.9 b	15.0±5.4 a	722.3±46 e
Onion	72.5±9.1 de	50.0±15.1 b	1428.0±232 g
Cotton	5.0±6.1 a	5.0±6.1 a	n.a.
P-value	< 0.0001	< 0.0001	< 0.0001

Fall armyworm host plants and development

All ten plant species tested in the laboratory allowed the fall armyworm to develop and complete its life cycle. However, the diet greatly influenced various developmental parameters (Table 1), including the durations of the larval ($K = 216.9$; $df = 9$; $P < 0.0001$), pupal ($K = 59.3$; $df = 9$; $P < 0.0001$) and adult ($K = 78.5$; $df = 9$; $P < 0.0001$) stages. Maize (15.1±0.7 days) and pearl millet (14.7±0.9 days) were the most favorable for larva development while tomato was the poorest host, leading to the longest larva development (30.1±3.1 days). Larval development included 6 stages with pearl millet, cowpea, groundnut, cotton, maize and onion while 7 stages were recorded on the other crops. The duration of pupal development was similar on all crops (between 8 and 9 days), except for cotton where it was longer (11 days). The duration of development to adult stage was longest on okra (14.0±4.4 days) than on maize (10.1±1.3 days), cowpea (9.0±1.4 days) and onion (9.2±1.3 days). The longevity of the fall armyworm was shorter when the larvae were fed on maize and pearl millet (36.8±0.6 and 36.7±1.0 days respectively) rather than tomato (51.8±2.2 days).

Larval diet greatly affected survival of larvae and fecundity of adults of the fall armyworm (Table 2). In the larval stage, the survival rates on okra and groundnut (82.5±14.6% and 80.0±6.1%, respectively) were higher than on cotton (5.0±6.1%). Pupal emergence rates were statistically similar for all crops (77.5 - 100%). No egg laying was recorded with adults from cotton because larvae survival was low and emerged adults were males only. In contrast, egg laying was recorded for female adults from the nine others crops. A significant difference between the mean numbers of eggs laid per female was recorded ($df=8$; $P<0.0001$).

A principal component analysis was performed to compare 9 crops (except cotton where there was no oviposition) using the following criteria: larval and adult development time, larval-adult survival rate and number of eggs laid (Fig. 4). With the exception of onion for which fecundity is very high despite the average survival rate, only larvae fed on maize, pearl millet and groundnut showed high survival and fecundity with a short larval and adult life span.

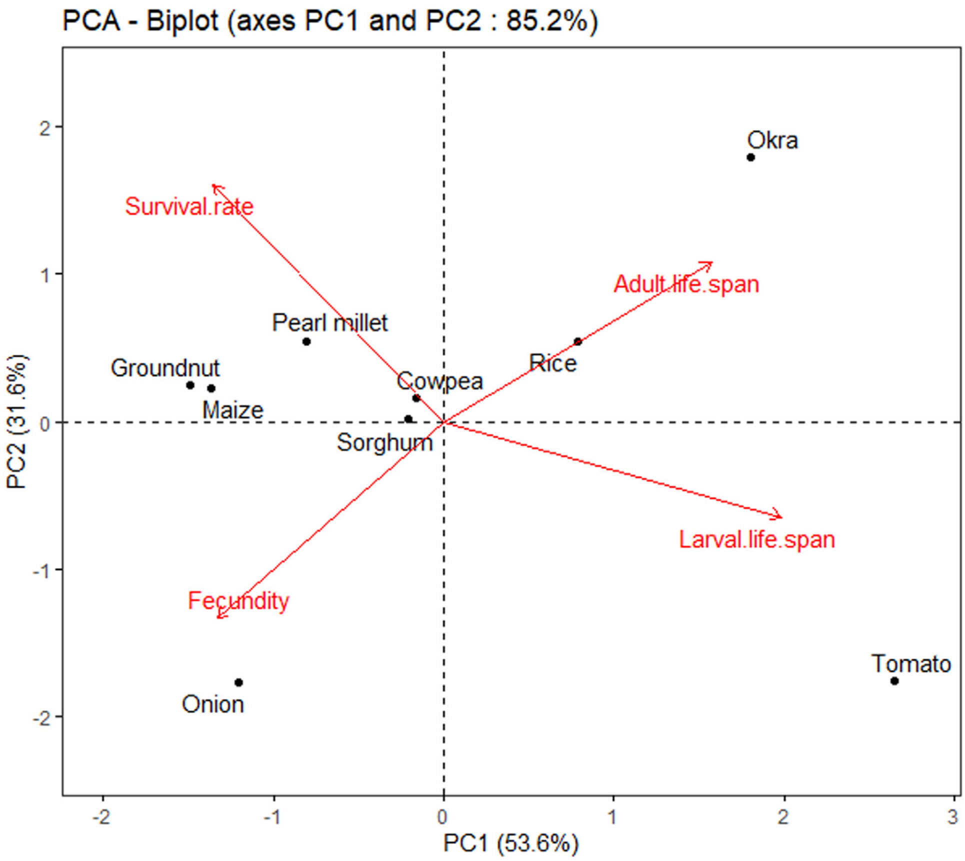

Fig. 4. Principal component analysis among the developmental variables of fall armyworm in different host species

Discussion

Maize production occurs mainly during the rainy season, but can also be settled during the dry season in irrigated perimeters, market gardens or lowlands in Western Burkina Faso. After the rains, maize planting is usually performed in June and July. Based on the moth catches at this period, maize seedlings should be carefuly monitored as they are very susceptible to damage from fall armyworm larvae. The increase in fall armyworm populations was synchronized with the major maize production periods at all sites in both the dry and rainy seasons. Adult catches reach their higher peak in August. This period generally corresponds to the 6 - 12 leaf stage of maize (V6 – V12) after which catches become less important. The same trends were observed in the dry season after maize planting. Similar results were obtained in a study conducted in Ghana during two successive rainy seasons [18]. For effective management of fall armyworm, it is important to concentrate insecticide applications when maize plants have not reached the flowering stage. Generally, pre-flowering maize leaves are more tender and susceptible to larval damage (particular for neonates) compared to older leaves. A high density of larvae per maize plant indicates that the larvae have not reached the advanced stages, as cannibalism within this species usually reduces the number to one larva per plant [23]. We also confirm that larva density decreases as the maize leaves begin to dry and the acorns develop [24].

This study reports that the presence of maize at any time of the year plays an important role in the abundance of the fall armyworm. The mean annual temperature (29°C) is favorable for fall armyworm development [7]. We showed that during the dry season, maize fields were more affected by the insect than during the rainy season (as regard to the proportion of infested plants), probably as a result of (i) the low availability of alternative hosts in the dry season, and (ii) the abundance of host plants and natural enemies in the rainy season [9]. A similar trend was observed in Mozambique, where the percentage of infested fields and infested plants per field was higher during the dry season [25]. Therefore, crop diversity is very important to reduce fall armyworm populations and to attract and maintain natural enemies that play an important role in the regulation of the pest. In the mid dry season (March-May) in the absence of maize, male adults of the fall armyworm were caught in low numbers. The insect would be able to feed on alternative plants, such as pearl millet [10]. Therefore, better detections can be achieved by monitoring the surrounding crops and non-crop plants.

In this study, we identified ten host plants of fall armyworm that allow it to develop and complete its life cycle. Although the fall armyworm is a highly polyphagous pest, its development is greatly impacted by the consumed plant [26]. With larva-to-adult survival rates ranging between 65 and 80%, mean fecundity of 700 - 1000 eggs per female, and a longevity of 36.7±1.0, 36.8±0.6 and 37.8±0.1 days; pearl millet, maize, and groundnut were respectively the most favorable hosts for fall armyworm development. As a result, three to four generations could occur on long-cycle maize, pearl millet and groundnut. In terms of control decisions, early planting and short-cycle varieties could allow farmers to avoid heavy infestations at the end of the cycle. Fall armyworm larvae typically complete six larval instars [7], but they may complete seven and very rarely eight depending on temperature and availability of the host plant [8]. In addition, several studies have shown that the older stages were the longest [27,28], most voracious [8,23] and least susceptible to insecticides [29]. Therefore, the early larval stages of fall armyworm should be the focus of the integrated management program. Using effective products, the best time to apply pesticide treatments is the first days after the emergence of neonates. Effective integrated management of this pest in Burkina Faso and areas with similar climatic conditions requires close monitoring of the pest in crops associated with maize or planted after maize harvests. Early detection (e.g., with pheromone traps), use of short-cycle varieties, and early planting will reduce fall armyworm damage.

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Authors contribution

BRA, WMS, FS, AHB-G, IS and FJV designed the study; BRA and WMS carried out field collection and realised the collection map; BRA, WMS and YB analysed the data; BRA and FJV wrote the manuscript with inputs from all authors; AHB-G, IS and FJV supervised the project. All authors reviewed and approved the manuscript before submission.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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References

[1] G. Goergen, P.L. Kumar, S.B. Sankung, A. Togola, M. Tamò, First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (J E Smith) (Lepidoptera, Noctuidae), a new alien invasive pest in West and Central Africa, PLoS One 11 (10) (2016) e0165632, doi:10.1371/journal.pone.0165632.
[2] Y.G. Tizie, C N'Guessan, Atelier de renformcement des capacités des Etats membres de la CEDEAO pour lutter contre l'invasion de Spodoptera frugiperda en Afrique de l'Ouest - Abuja (Nigeria) du 5 au 10 Septembre 2017, Compte-rendu d'atelier, ANADER - Agence Nationale d'Appui au Développement Rural, Abidjan, Côte d'Ivoire, 2017 Online at http://www.anader.ci/focus/Compte%20rendu%20de%20l%27atelier%20d%27Abuja%20POUR%20FOCUS.pdf accessed 18 June 2020.
[3] I. Rwomushana, M.L. Bateman, T. Beale, P. Beseh, K. Cameron, M. Chiluba, V. Clottey, T. Davis, R.K. Day, R. Early, J. Godwin, P. Gonzalez-Moreno, M. Kansiime, M. Kenis, F. Makale, I. Mugambi, S. Murphy, W. Nunda, N.A. Phiri, C. Pratt, J. Tambo, Fall Armyworm: Impacts and Implications for Africa, CABI Evidence Note Update; CABI, Wallingford, UK, 2018 Online athttps://www.invasive-species.org/wp-content/uploads/sites/2/2019/02/FAW-Evidence-Note-October-2018.pdf accessed 7 July 2020.
[4] F. Baudron, M.A. Zaman-Allah, I. Chaipa, N. Chari, P. Chinwada, Understanding the factors influencing fall armyworm (*Spodoptera frugiperda* J.E. Smith) damage in African smallholder maize fields and quantifying its impact on yield. A case study in Eastern Zimbabwe, Crop Prot. 120 (2019) 141–150, doi:10.1016/j.cropro.2019.01.028.
[5] D.G. Montezano, A. Specht, D.R. Sosa-Gómez, V.F. Roque-Specht, J.C. Sousa-Silva, S.V Paula-Moraes, J.A. Peterson, T.E. Hunt, Host plants of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in the Americas, African Entomol. 26 (2) (2018) 286–300, doi:10.4001/003.026.0286.
[6] R. Early, P. González-Moreno, S.T. Murphy, R.K. Day, Forecasting the global extent of invasion of the cereal pest *Spodoptera frugiperda*, the fall armyworm, NeoBiota 40 (2018) 25–50, doi:10.3897/neobiota.40.28165.
[7] B.M. Prasanna, J.E. Huesing, R. Eddy, V.M. Peschke (Eds.), Fall Armyworm in Africa: A Guide for Integrated Pest Management, CIMMYT, Mexico, CDMX, 2018.
[8] P. Luginbill, in: The fall armyworm, 34, United States Department of Agriculture, Technical Bulletin, 1928, pp. 1–91. https://naldc.nal.usda.gov/download/CAT90913266/PDF. Online at.
[9] M.E. Cammell, J.D. Knight, Effects of climatic change on the population dynamics of crop pests, In *Adv. Ecol. Res.* 22 (1992) 117–162, doi:10.1016/S0065-2504(08)60135-X.
[10] B.M. Favetti, T.L. Braga-Santos, A. Massarolli, A. Specht, A.R. Butnariu, Pearl millet: A green bridge for lepidopteran pests, J. Agric. Sci. 9 (6) (2017) 92–97, doi:10.5539/jas.v9n6p92.
[11] D. Babendreier, L.K. Agboyi, P. Beseh, M. Osae, J. Nboyine, S.E.K. Ofori, M. Kenis, The efficacy of alternative, environmentally friendly plant protection measures for control of fall armyworm, *Spodoptera frugiperda*, in maize, Insects 240 (11) (2020), doi:10.3390/insects11040240.
[12] A.J. Hruska, Fall armyworm (*Spodoptera frugiperda*) management by smallholders, CAB Rev. 14 (043) (2019) 1–11, doi:10.1079/PAVSNNR201914043.
[13] T. Liu, J. Wang, X. Hu, J. Feng, Land-use change drives present and future distributions of Fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), Sci. Total Environ. 706 (2020) 135872, doi:10.1016/j.scitotenv.2019.135872.
[14] B. Sisay, T. Tefera, M. Wakgari, G. Ayalew, E. Mendesil, The efficacy of selected synthetic insecticides and botanicals against fall armyworm, *Spodoptera frugiperda*, in maize, Insects 10 (45) (2019) 1–14, doi:10.3390/insects10020045.
[15] L.K. Agboyi, G. Goergen, P. Beseh, S.A. Mensah, V.A. Clottey, R. Glikpo, M. Kenis, Parasitoid complex of fall armyworm, *Spodoptera frugiperda*, in Ghana and Benin, Insects 11 (68) (2020) 1–15, doi:10.3390/insects11020068.

[16] A. Sawadogo, L. Kouadio, F. Traoré, S.J. Zwart, T. Hessels, K.S. Gündoğdu, Spatiotemporal assessment of irrigation performance of the Kou Valley irrigation scheme in Burkina Faso using satellite remote sensing-derived indicators, ISPRS Int. J. Geo-Informat. 9 (8) (2020), doi:10.3390/ijgi9080484.
[17] J. Wellens, M. Nitcheu, F. Traore, B. Tychon, A public–private partnership experience in the management of an irrigation scheme using decision-support tools in Burkina Faso, Agric. Water Manage. 116 (2013) 1–11, doi:10.1016/j.agwat.2012.09.013.
[18] J.A. Nboyine, F. Kusi, M. Abudulai, B.K. Badii, M. Zakaria, G.B. Adu, A. Haruna, A. Seidu, V. Osei, S. Alhasan, A. Yahaya, A new pest, *Spodoptera frugiperda* (J.E. Smith), in tropical Africa: Its seasonal dynamics and damage in maize fields in northern Ghana, Crop Prot. 127 (2020) 104960, doi:10.1016/j.cropro.2019.104960.
[19] B. Ibrahim, H. Karambiri, J. Polcher, H. Yacouba, P. Ribstein, Changes in rainfall regime over Burkina Faso under the climate change conditions simulated by 5 regional climate models, Clim. Dyn. 42 (2014) 1363–1381, doi:10.1007/s00382-013-1837-2.
[20] InfoclimatClimatologie de l'année 2020 à Bobo-Dioulasso - Infoclimat, 2021 Online athttps://www.infoclimat.fr/climatologie/annee/2020/bobo-dioulasso/valeurs/65510.html%0A accessed 14 May 2021.
[21] B.R. Ahissou, W.M. Sawadogo, A.H. Bokonon-Ganta, I. Somda, M.-P. Kestemont, F.J. Verheggen, Baseline toxicity data of different insecticides against the fall armyworm *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) and control failure likelihood estimation in Burkina Faso, African Entomology 29 (2) (2021) 435–444, doi:10.4001/003.029.0435.
[22] R Core TeamR: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2021 URLhttps://www.R-project.org/.
[23] Q. Ren, M. Haseeb, J. Fan, P. Wu, T. Tian, R. Zhang, Functional response and intraspecific competition in the fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae), Insects (806) (2020) 11, doi:10.3390/insects11110806.
[24] L.E.R. Pannuti, E.L.L. Baldin, T.E. Hunt, S.V. Paula-Moraes, On-plant larval movement and feeding behavior of fall armyworm (Lepidoptera: Noctuidae) on reproductive corn stages, Environ. Entomol. 45 (1) (2016) 192–200, doi:10.1093/ee/nvv159.
[25] A. Caniço, A. Mexia, L. Santos, Seasonal dynamics of the alien invasive insect pest *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) in Manica Province, Central Mozambique, Insects 11 (8) (2020) 512, doi:10.3390/insects11080512.
[26] D.M. da Silva, A.de F. Bueno, K. Andrade, C.dos S. Stecca, P.M. Oliveira, J. Neves, M.C.N de Oliveira, Biology and nutrition of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) fed on different food sources, Scientia Agricola 74 (1) (2017) 18–31, doi:10.1590/1678-992X-2015-0160.
[27] R.T. Hutasoit, S.H. Kalqutny, I.N. Widiarta, Spatial distribution pattern, bionomic, and demographic parameters of a new invasive species of armyworm *Spodoptera frugiperda* (Lepidoptera; Noctuidae) in maize of South Sumatra, Indonesia, Biodiversitas 21 (8) (2020) 3576–3582, doi:10.13057/biodiv/d210821.
[28] L. Wu, C. Zhou, G. Long, X. Yang, Z. Wei, Liao, L. Ying-jiang, H. Yang, C Hu, Fitness of fall armyworm, *Spodoptera frugiperda* to three solanaceous vegetables, J. Integr. Agric. 20 (3) (2021) 755–763, doi:10.1016/S2095-3119(20)63476-1.
[29] G.M. Ghidiu, J.T. Andaloro, The relationship between fall armyworm (Lepidoptera: Noctuidae) instar and susceptibility to insecticides applied to sweet corn, Florida Entomol. 76 (4) (1993) 549–555, doi:10.2307/3495784.