Scientific African 31 (2026) e03158

Contents lists available at ScienceDirect

Scientific African

journal homepage: www.elsevier.com/locate/sciaf

Risk Assessment of the fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae) invasion of Morocco

Khalid Khfif[a,*], Awa Ndiyae[b], Kofi Frimpong-Anin[c], Assienin Hauverset N'guessan[d], Timothy Oluwafemi Ajiboye[e], Akira Otuka[f]

[a] *Laboratory of Entomology, Research Unit on Nuclear Techniques, Environment, and Quality, National Institute for Agricultural Research (INRA), 78 Bd. Sidi Med. Ben Abdellah, 90010 Tangier, Morocco*
[b] *Senegalese Institute of Agricultural Research (ISRA), Dakar, Senegal*
[c] *CSIR-Crops Research Institute, Kumasi, Ghana*
[d] *National Centre for Agricultural Research (CNRA), Abidjan, Côte d'Ivoire*
[e] *National Centre for Genetic Resources and Biotechnology (NACGRAB), Moor Plantation, Apata, Ibadan, Oyo State, Nigeria*
[f] *Institute for Plant Protection, National Agriculture and Food Research Organization (NARO), Kōshi, Kumamoto 861-1102, Japan*

A R T I C L E I N F O

Editor: DR B Gyampoh

Keywords:
Spodoptera frugiperda
Invasive pest
Risk assessment
Migration modeling
West Africa

A B S T R A C T

The fall armyworm (FAW) *Spodoptera frugiperda*, is a polyphagous pest, causing serious economic damage to plant production and consequent social implications in Africa. As FAW is a migratory moth that was first confirmed in western African countries in early 2016, it quickly spread to most African continent. However, no FAW has been found in Morocco so far. In this study, we assessed the migration risk of the FAW to Morocco by applying a trajectory modeling approach to simulate potential flight paths from several locations where the pest is currently established. Our findings indicated that the majority of simulated terminal points originating from the Mauritanian trap site near the Moroccan border were concentrated over the Atlantic Ocean, southern Mauritania, and northern Senegal, with only a few reaching Moroccan territory. The risk of FAW invasion from the south appears low, as the arid desert regions of southern Morocco lack suitable host plants, and the combination of high temperatures and drought stress likely limits the pest's survival and movement. Therefore, FAW monitoring efforts should be prioritized in areas facing the Canary Islands, where both host plants and favorable climatic conditions exist. Although the primary focus of this study was to assess FAW invasion risk to Morocco, broader wind dynamics across Africa were briefly considered to provide regional context.

Introduction

The fall armyworm (FAW) *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), is a polyphagous pest that feeds on large numbers of plants, with strong preference to the Poaceae (maize, rice, sorghum and sugarcane), but also to different species of Asteraceae and Fabaceae. It, therefore, is causing a serious economic damages to these plants production with strong social implication [1–9].

The FAW is a migratory moth that can migrate hundreds of kilometers per one night and fly >500 km per one generation [10]. The

* Corresponding author.
E-mail address: khalid.khfif@inra.ma (K. Khfif).

https://doi.org/10.1016/j.sciaf.2025.e03158
Received 25 November 2024; Received in revised form 14 October 2025; Accepted 29 December 2025
Available online 29 December 2025

moth may fly overseas for >1000 km in 36 h maximally [11–13]. Its high movement ability, diverse host range, and lack of diapause [14], make its control more complicated, resulting in its quick spread all around Africa and the world in general.

FAW was first detected in West Africa in early 2016 [15] and rapidly spread across most tropical African countries within two years [16–19]. It was subsequently confirmed in Mali [20], Egypt [21], and Mauritania [22], extending the pest's range into North Africa. By 2021, FAW had reached the Canary Islands [23,24], and later appeared in Türkiye [25], Greece [26], and Romania [27]. This rapid expansion, driven by both natural migration and human-mediated movement [28,29], underscores the importance of early detection and monitoring in countries like Morocco that are adjacent to affected regions.

In Morocco, therefore, the pest is considered as a quarantine insect, that the government is surveying in a national early detection program using pheromone traps and field surveys. Furthermore, the regulations are applied on import of the insect host plants and FAW pheromones. The farmers with support of Moroccan governmental institutions are also engaged to collaborate in formation of the survey plan to detect any early introduction of *S. frugiperda*.

The FAW's risk to invade southern Europe via northern African countries such as Morocco and Tunisia with the assistance of winds was discussed by [29]. Their results showed that the risk of FAW invasion between years was highly consistent, and the coastal areas of northern Africa and southern Europe were most suitable for the expansion of the FAW, and Spain and Italy were estimated to have the highest risk of invasion. Therefore, it is an urgent issue to forecast FAW's possible immigration areas in Morocco, which helps early deployment of pest management measurements and strengthen monitoring in possible high-risk zones.

The use of numerical trajectory models is an effective method for simulating migratory pest's flight trajectories. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) has been used to study the long-distance transport of airborne thrips with backward trajectories [30], and to simulate the long-distance migration of malaria mosquitoes in the Sahel [31]. Furthermore, backward trajectories were investigated with HYSPLIT to study the FAW migration across the Lesser Antilles [32], and to simulate the multi-generational FAW migration dynamics in the USA [33], and to assess the FAW migration risk from north Africa to southern Europe from April to August 2016–2022 [29].

Spodoptera frugiperda migration risk analysis is important to Morocco's country plant protection policy. Although the pest has not been detected in the country yet, its rapid movement across Africa and recent discoveries in the Canary Islands and southern Europe indicated a looming regional threat. Mapping potential migration corridors enables the authorities to anticipate invasion scenarios, determine surveillance priorities at high-risk locations, and improve border and quarantine inspection. This study thus provided scientific proof for Morocco's ambition to protect its agriculture and biodiversity against possible FAW infestation using early warning and preventive management practices.

This study evaluated the FAW's migration risk to Morocco. Its forward trajectories from different starting points in western Africa where the moth occurs were calculated. To support the understanding of potential migration risk to Morocco, selected regional wind systems relevant to Western Africa were examined. Broader patterns across Africa were discussed only briefly, and will be the subject of a separate study.

Materials and methods

FAW trap data

To select starting points of trajectories, FAW trap data in western Africa, were obtained from FAW Monitoring and Early Warning System (FAMEWS) global platform, (available under the FAO authorization on: https://www.fao.org/fall-armyworm/monitoring-tools/famews-global-platform/en/). The data used in the present study range from April 2021 to December 2023, which is the most recent full dataset up to the analysis time. Data from neighboring countries of Morocco were included if FAW were regularly caught and recorded on the FAMEWS platform up to August 2024. Based on this selection, the starting points were chosen in Mauritania (17.99°E, 15.97°S), Cabo Verde (15.09°E, 23.66°S), Guinea (11.33°E, 12.33°S) and Burkina Faso (11.36°E, 4.41°S) for the risk assessment of FAW migration to Morocco. It must be pointed out that FAW trap data were not utilized for quantitative comparison across locations of population abundance because numbers caught depend on trap number and type, trap status, and local crop availability. These data only came in handy to identify representative locations where FAW was consistently caught to establish realistic starting points for the trajectory modeling. This approach minimizes the impact of local variations in trapping and addresses regional migration potential that can be used for Morocco's invasion risk analysis. For consistency, only records with both valid capture numbers and complete spatial-temporal information were retained. In cases like Burkina Faso, records prior to late 2020 were excluded from analysis due to inconsistent location tagging.

Calculation of the FAW trajectory

The HYSPLIT ver. 5.3.0 trajectory model, a Windows-based public version developed by the Air Resources Laboratory of the U.S. National Oceanic and Atmospheric Administration (NOAA), was used to calculate FAW's forward trajectories [34–36]. The forward trajectories were calculated with the hyts_std program in the HYSPLIT System. The meteorological data used were the U.S. National Center for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS) one-degree three-hourly archive data from 2004 to the present (archive information: https://www.ready.noaa.gov/gdas1.php).

As FAW is a nocturnal moth, it generally takes off at dusk for a nighttime flight, keeps flying until the following dawn and terminates its flight [37,38]. The flight duration of the nighttime flight was set to be 10 h, beginning at 20:00 h (GMT) for Mauritania, Guinea and Burkina Faso and 19:00 h (GMT-1) for Cape Verde, in the evening and ending at 06:00 h (GMT) for Mauritania, Guinea and

Burkina Faso and 5:00 h (GMT-1) for Cape Verde, in the following morning. Multiple trajectories with different starting locations and heights were calculated [13,29].

For each starting location, forward trajectories were calculated from six altitudes (100, 300, 600, 1000, 1200, and 1500 m above sea level), generating six trajectories per day per site. This resulted in a total of 2190 trajectories per starting point for the year 2023 (6 per day × 365 days). These altitudes were selected based on documented noctuid moth flight behaviors in prior studies [11,13]. A single representative trap location was chosen in each country (Mauritania, Cape Verde, Guinea, and Burkina Faso) based on consistently high FAW capture levels and proximity to Morocco. As in Wang et al. [29], we used the isobaric option in HYSPLIT, meaning that vertical displacement was not simulated trajectories were assumed to remain at constant pressure levels throughout the flight.

A FAW's horizontal flight speed was assumed to be 3.0 m/s in the lee direction of wind [39]. During the trajectory calculation, if ambient temperature at any hourly node of a flight trajectory dropped below a threshold cool temperature of T_c, the trajectory was determined invalid and removed. Ambient temperature at hourly node of each trajectory was checked whether it was $\geq 13.1\ ^{\circ}C$ (T_c), at

Fig. 1. Localization of FAW traps with positive captures are in blue in Cape Verde, Mauritania, Guinea and Burkina Faso. Four starting points localization are in red [41].

which half of FAW stop their wing-beating at a due to coldness [12]. When all the ambient temperatures along a trajectory are equal to or above T_c, the trajectory was determined to be valid. The terminal points of all valid trajectories were aggregated within grid cells measuring 0.25° × 0.25° (longitude × latitude) to calculate monthly frequency distributions. This frequency represents the number of terminal points falling in each grid cell and may include non-integer values because it reflects the average number of TPs per grid cell per month. The frequency was calculated with the *trajfreq* program in the HYSPLIT System [40].

Wind climatology map

Wind vector maps for monthly average horizontal wind (U and V-component) at a pressure level of 850 hPa (about 1500 m above sea level) were generated using the ERA5 monthly averaged data on pressure levels (archive information: https://cds.climate.

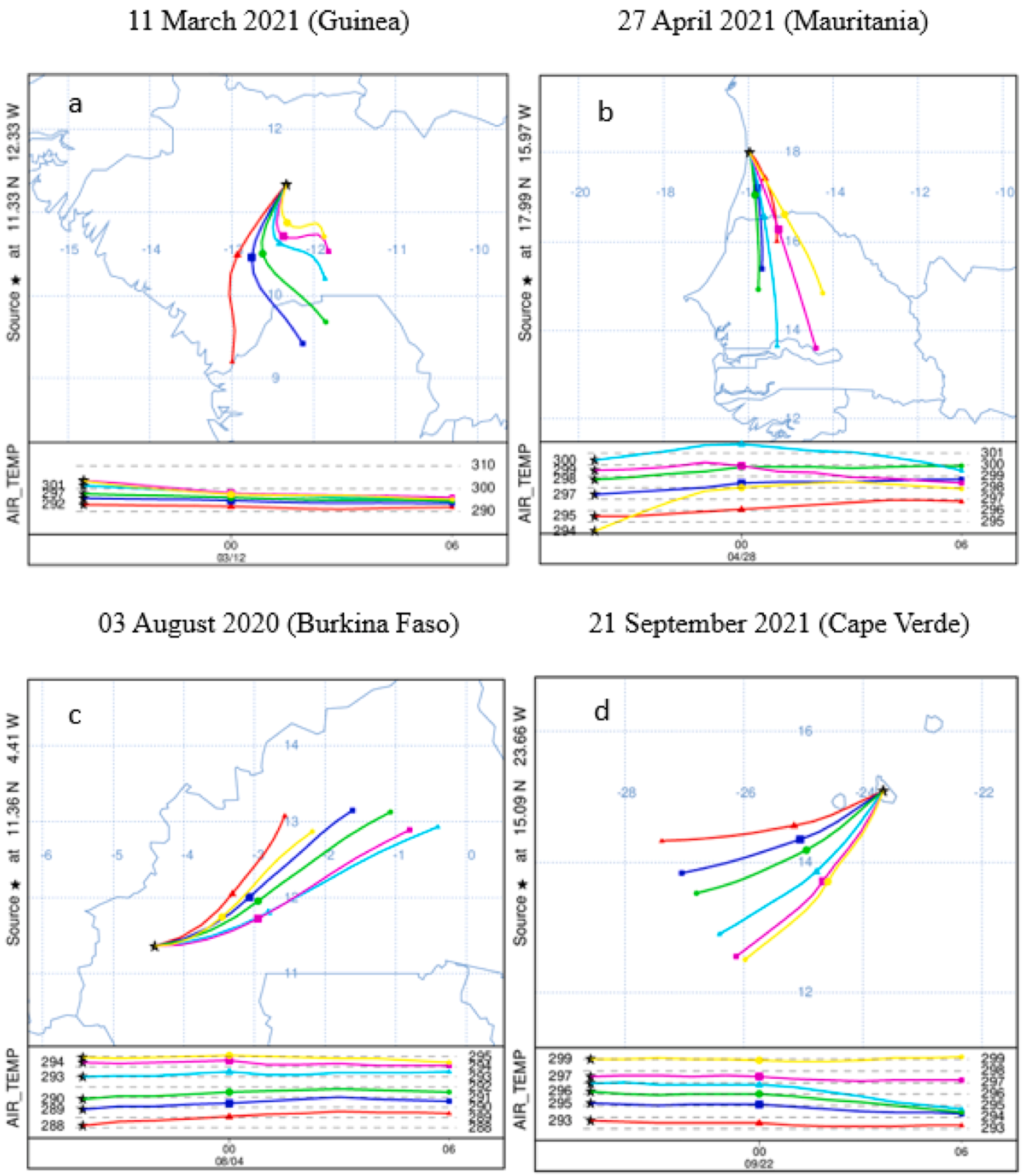

Fig. 2. FAW forward trajectories from (a) Burkina Faso, (b) Guinea, (c) Mauritania, and (d) Cabo Verde at selected dates and six starting heights (100, 300, 600, 1000, 1200, and 1500 m above sea level). Trajectory colors indicate the ambient air temperature along the flight path. Cooler temperatures generally correspond to higher flight altitudes.

copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=overview). The maps were made with Panoply Data Viewer, Version 5.4.3 (source: National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies; https://www.giss.nasa.gov/tools/panoply/). Maps covering western Africa, an area neighboring Morocco were made for January to December 2023, and maps covering the whole Africa for January 2016 to December 2018 (supplementary information). The latter wide maps were used to discuss the FAW's rapid expansion in Africa after the initial invasion.

Data analysis tools

All analyses were conducted based on migration trajectory modeling and processing FAW trap data. The HYSPLIT model (version 5.3.0; NOAA Air Resources Laboratory, USA) was used to calculate the forward trajectories. The outputs of trajectory and wind data were examined and plotted using Panoply Data Viewer (version 5.4.3; NASA Goddard Institute for Space Studies). Descriptive data handling, mapping, and figure preparation were carried out with Microsoft Excel (Office 365) and R software (version 4.5.1). Map layouts and figure design were finalized using Panoply Data Viewer (version 5.4.3) and Microsoft PowerPoint (Office 365) to assemble legends, scale bars, and annotations.

Results and discussion

The FAW trap data recorded by FAO (2024) in Mauritania adjacent to Morocco (Fig. 1), from April 27th, 2021 to December 14th, 2023 showed that Brakna District was a site with the largest total capture of 2078 FAW adult moths, followed by Gorgol with 212 FAW adult moths, Assaba (110), Trarza (95) and Guidimaka (2). Details about localization, timing and trap data by country are available on FAMEWS global platform under FAO authorization.

In Cape Verde, FAW captures were recorded from October 25th, 2018 to August 24th, 2022, with the highest number in the district

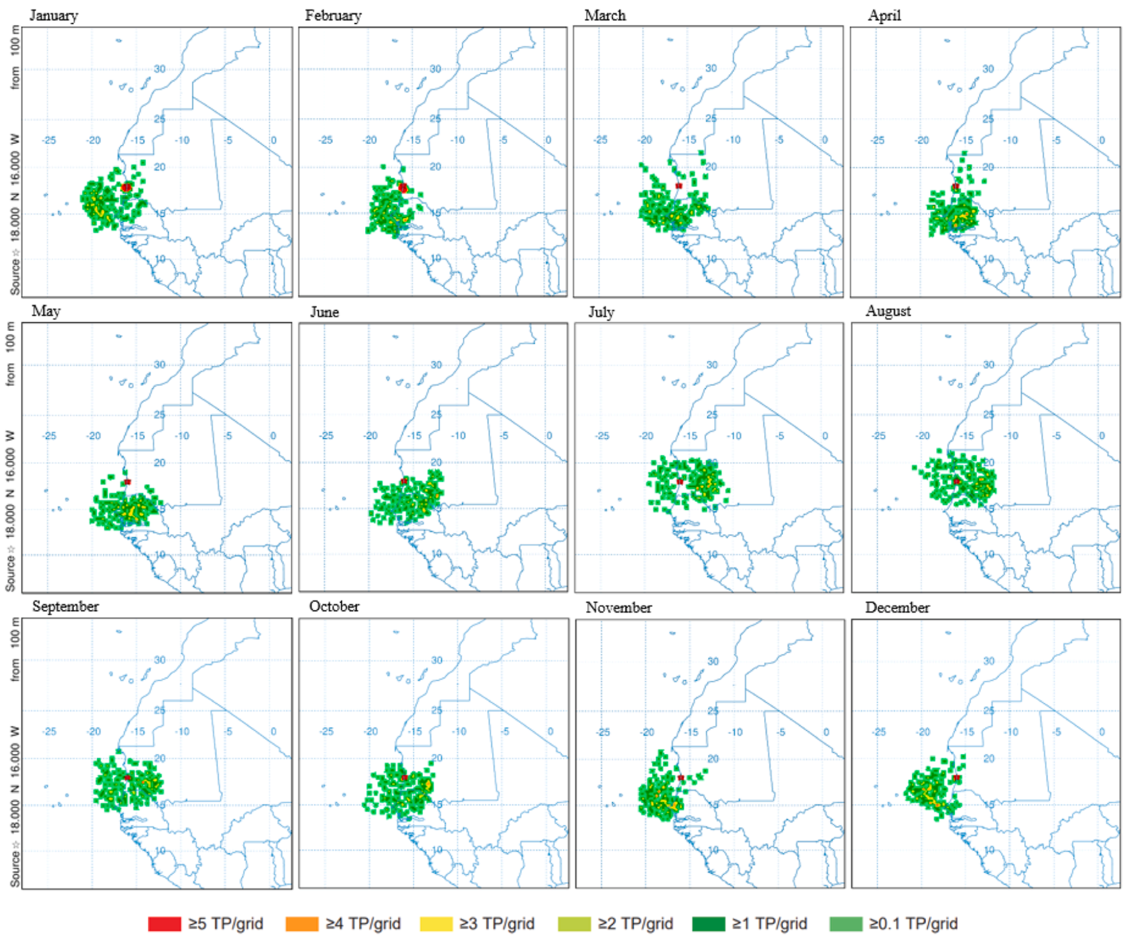

Fig. 3. Monthly distribution of FAW terminal points (TPs) from forward trajectories starting at Mauritania at 1500 m height in 2023. The color scale indicates the frequency of valid terminal points (TPs) per 0.25° × 0.25° grid cell, averaged over the month. Frequencies may include decimal values as they represent monthly averages across 6 trajectories per day (~180 per month). A red point marks the trajectory starting location.

of Porto Novo (16,944 FAW adult moths), followed by Santa Catarina (15,603), São Filipe (9553), Ribeira Grande (3771), São Vicente (3599), Santa Cruz (3165), Praia (1380), Brava (288), Paul (200), and Tarrafal (66). In Guinea, FAW captures were recorded from January 17th, 2020 to August 8th, 2021, mainly in the district of Kindia (398 FAW adult moths), followed by Kankan (292), Nzérékoré (60), Conakry (32), Labé (8), Faranah (6), and Boké (2). In Burkina Faso, captures were recorded from November 23rd, 2020 to August 17th, 2022, with a total of 46 FAW adult moths, mainly in the Central West district (43) and the Southwest (3). According to Ahissou et al. [42], the annual dynamics of the FAW population in Burkina Faso showed two peaks in January and August 2020 in the province of Houet. FAO data [43] indicated population peaks in January, February, and March in Guinea; from November to March in Cabo Verde and in February, March, and June in Burkina Faso. FAW captures in Mauritania were generally concentrated between September and December, although notable peaks were also observed in some early months such as January 2023, reflecting year-to-year variability in seasonal dynamics [43]. While this dataset from the FAMEWS platform provides valuable insights in Western Africa, its coverage is known to be spatially and temporally patchy, with some countries reporting very few records in certain years. Nevertheless, variability in trap type, density, and monitoring duration across sites may have influenced the recorded adult counts, which were therefore interpreted only as presence indicators rather than absolute measures of abundance. Despite this limitation, the

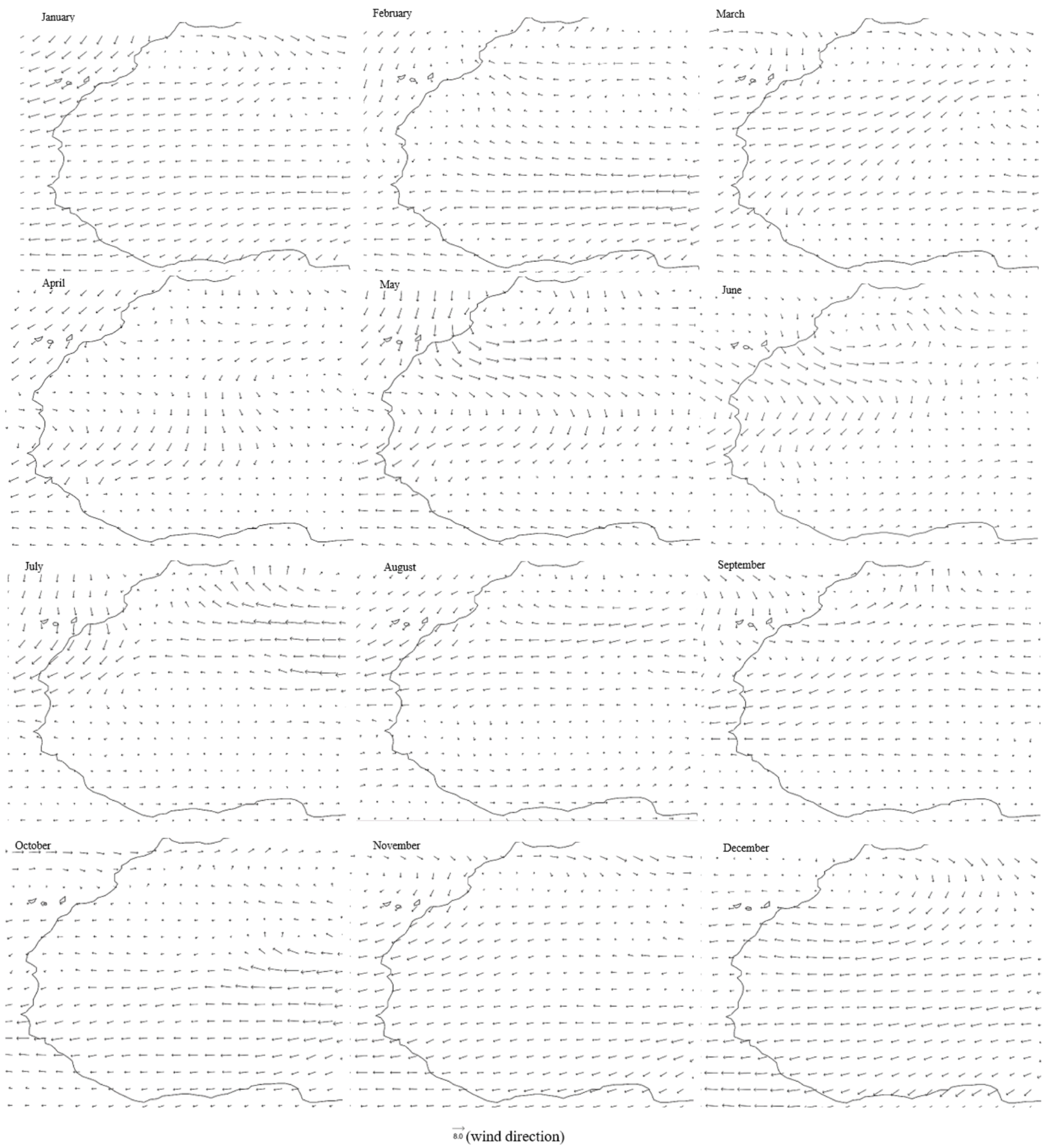

Fig. 4. Monthly mean of speed and wind direction in 2023 at 850 hPa.

data remains the most comprehensive available source to inform migration modeling.

Fig. 2 showed examples forward trajectories from one date for each of the four source countries, selected based on available trap records with reliable spatial data. These examples were intended to illustrate the modeling approach and typical directional patterns, rather than represent seasonal peaks in FAW abundance.

Due to northerly winds in spring, FAW present at Guinea and Mauritania could take flight pathways to the south (Fig. 2a, b). FAW present at Bobo-Dioulasso area (Burkina Faso) in summer could take flight pathways to the east (Fig. 2c). However, in autumn and winter, northeasterly winds could assist FAW in Assomada area (Cape Verde) on 21st September 2021 to fly to the southwest (Fig. 2d).

The Fig. 3 showed the spatial distribution of valid terminal points (TPs) at Nouakchott trap site, Mauritania, at 1500 m height in 2023, which went mainly to the south. Each color represents the number of TPs within a 0.25° × 0.25° grid cell. These frequencies were calculated monthly by aggregating the endpoints of all valid trajectories. Because the values represent monthly averages across multiple days, frequencies may include decimal values (e.g., ≥0.1/grid), especially in cells with low trajectory density. Although forward trajectories were simulated for six different starting heights (100, 300, 600, 1000, 1200, and 1500 m), the spatial distribution patterns of terminal points were broadly consistent across altitudes. The 1500 m height was selected for detailed presentation as it corresponds to a typical migratory flight level for noctuid moths and often produced clearer and more extended trajectories due to stronger prevailing winds [44]. Depending on the season, the direction of the terminal point changed between southwest and southeast. This can be explained by the wind direction that changes from northeasterly in autumn/winter to westerly in spring/summer over the site (Fig. 4). Minor variations were observed at lower altitudes in terms of trajectory length and spread, but these did not alter the main interpretation. Additionally, trajectory patterns from other nearby starting points within each country showed no major deviations from those presented here.

Overall, the high concentration of the terminal points (the final locations reached by simulated FAW flights) from Mauritania was distributed mostly over the Atlantic Ocean, southern Mauritania, and northern Senegal (Fig. 3). The number of the terminal point on Morocco's territory was very few. The terminal points of the FAW short trajectories during 2023 after 10 h flights from dusk starting at

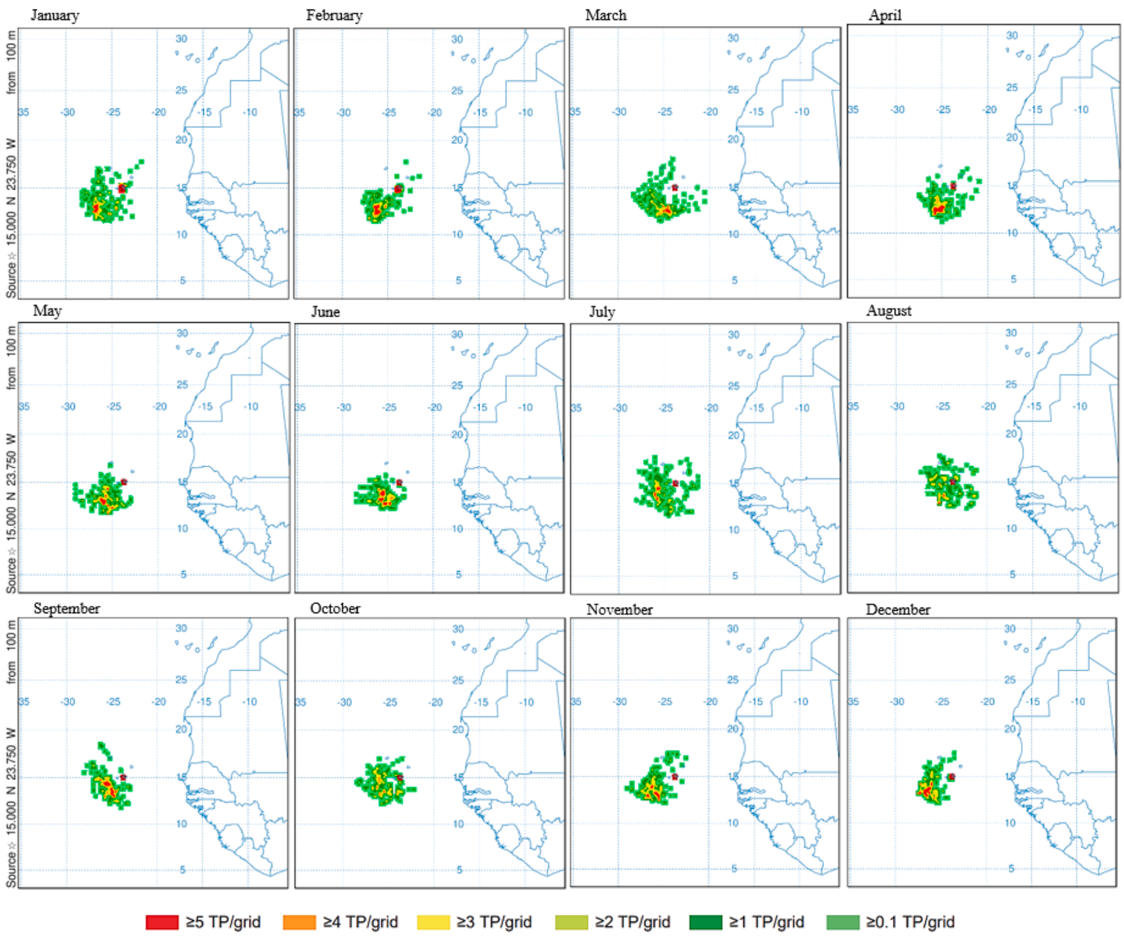

Fig. 5. Monthly distribution of FAW terminal points (TPs) from forward trajectories starting at Cabo Verde at 1500 m height in 2023. The color scale indicates the frequency of valid terminal points (TPs) per 0.25° × 0.25° grid cell, averaged over the month. Frequencies may include decimal values as they represent monthly averages across 6 trajectories per day (~180 per month). A red point marks the trajectory starting location.

Assomada trap site, Cape Verde, at 1500 m heights, which went mainly to south-west (Fig. 5). This is reason of the northeasterly wind that can take the FAW mostly south-west far away from Cabo Verde Islands (Fig. 4). Overall, the high concentration of the terminal points was not distributed on Morocco but was distributed in south-west over the Atlantic Ocean from Cabo Verde islands.

The terminal points of the FAW short trajectories during 2023 after 10 h flights from dusk starting at Labé area trap site, Guinea at 1500 m heights (Fig. 6), which went mainly to north-east direction in spring and summer due to the northeasterly wind and to south-west direction in autumn and winter due to westerly wind (Fig. 4). Overall, the high concentration of the terminal points was not distributed on Morocco but was distributed mostly over west of Guinean and south-east of Senegal and west of Mali.

The terminal points of the FAW short trajectories during 2023 after 10 h flights from dusk starting at Bobo-Dioulasso area trap site, Burkina Faso at 1500 m heights (Fig. 7), which went mainly to north-east direction by spring and summer due to the northeasterly wind and to south-west direction by autumn and winter due to westerly wind (Fig. 4). Overall, the high concentration of the terminal points was not distributed on Morocco but was distributed mostly over north of Côte d'Ivoire and Burkina Faso and south of Mali.

Broader patterns of FAW migration across Africa, influenced by seasonal wind dynamics, were presented in the supplementary material for regional context. However, these patterns were not central to the present risk assessment for Morocco. A separate study will be needed to analyze the complex wind and genomic-driven spread of FAW across Africa, as highlighted by Tay et al. [45].

As the FAW's presence on the Canary Islands was confirmed since February 2021 [23,24], yet with no data available in the FAMEWS platform [43], a daily forward trajectories were simulated from a site near Las Palmas, Gran Canaria (28.10°N, 15.41°W) during 2023 (Fig. 8), 2022 and 2021 (supplementary material). These simulations showed that most trajectories were directed to the southwest, away from the Moroccan coast. This pattern reflected the dominant northeasterly winds in the region. The results suggested that the likelihood of FAW reaching Morocco from the Canary Islands via wind-assisted migration is relatively low. The absence of FAMEWS trap data from the Canary Islands does not limit these findings, as the simulations were based solely on atmospheric conditions and modeled moth behavior.

Although a few FAW forward trajectories terminated within Moroccan territory, these endpoints were very limited in number and

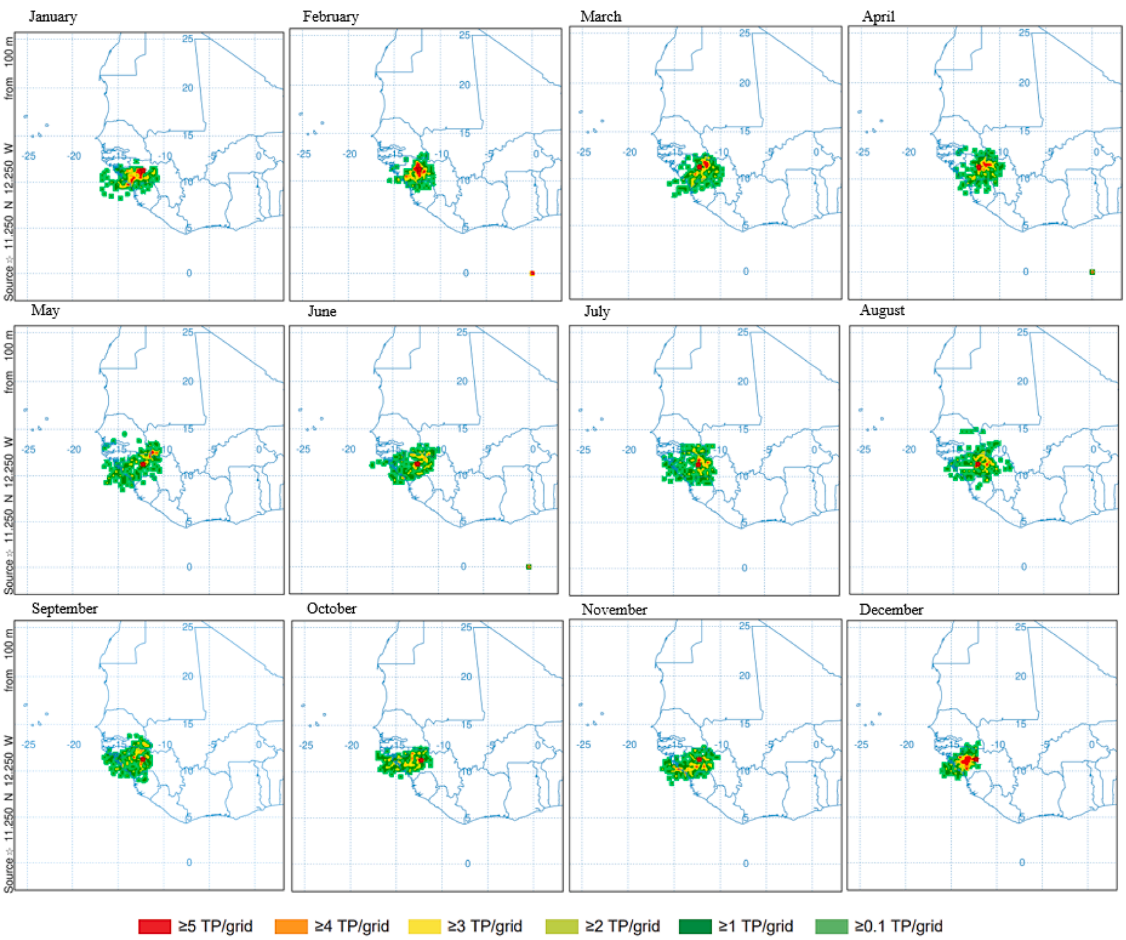

Fig. 6. Monthly distribution of FAW terminal points (TPs) from forward trajectories starting at Guinea at 1500 m height in 2023. The color scale indicates the frequency of valid terminal points (TPs) per 0.25° × 0.25° grid cell, averaged over the month. Frequencies may include decimal values as they represent monthly averages across 6 trajectories per day (~180 per month). A red point marks the trajectory starting location.

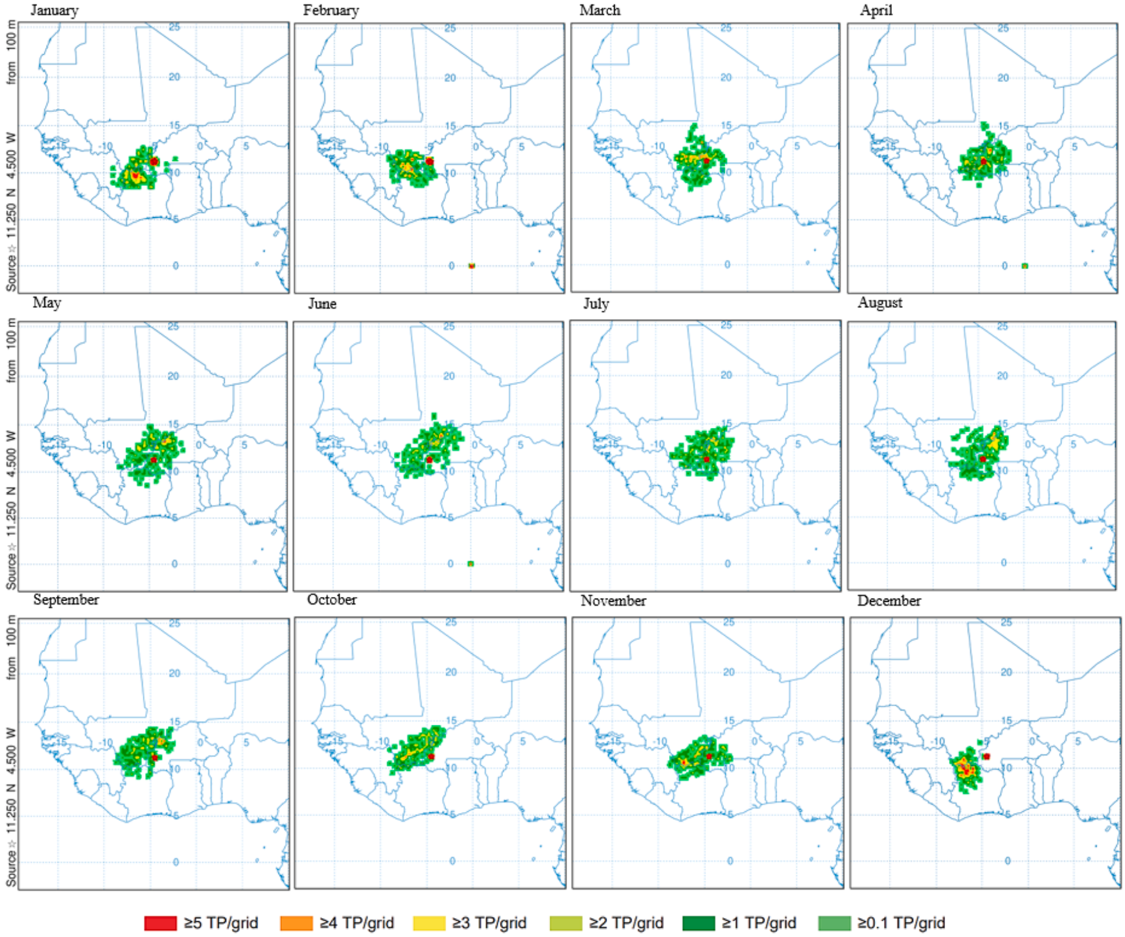

Fig. 7. Monthly distribution of FAW terminal points (TPs) from forward trajectories starting at Burkina Faso at 1500 m height in 2023. The color scale indicates the frequency of valid terminal points (TPs) per 0.25° × 0.25° grid cell, averaged over the month. Frequencies may include decimal values as they represent monthly averages across 6 trajectories per day (~180 per month). A red point marks the trajectory starting location.

spatially dispersed. Most were located in the extreme southwest of the country, in areas characterized by very low NDVI values throughout the year (supplementary material). These regions lack irrigated agriculture or consistent vegetation cover and are not known to support FAW host plants. Furthermore, previously published environmental suitability models [7,46] similarly indicated that most of Morocco, particularly its southern and interior regions, is poorly suited to FAW survival. Therefore, even when rare trajectories reach Moroccan territory, the likelihood of successful establishment remains low.

Wang et al. [29] used the HYSPLIT model to simulate the FAW possible migration pathway from northern Africa to southern Europe. They created >680 thousand trajectories and only 4.9 % of the trajectories that were successfully entered the European territory, which makes the FAW invasion to Europe a small probability event. Although our forward trajectory simulations from the Canary Islands generally indicated a low likelihood of FAW reaching Morocco, due to prevailing northeasterly winds, this risk cannot be entirely excluded. FAW moths were capable of sustained flight for up to 36 h [11], and under certain meteorological conditions, regional wind systems such as the Leveche (a local wind that affects south-eastern Spain in summer) or Sirocco (a hot and subsequently humid southeast to southwest winds over northern Africa) could facilitate atypical migration routes toward the Moroccan coast. These specific wind events were not explicitly included in our trajectory modeling but are noted here to highlight the potential for rare, wind-assisted migration [29].

The risk of FAW to invade Morocco from the south stays lower as there are no FAW host plant in the Moroccan desert, and if the FAW flights continuously (night and day), the highest temperature and drought stress can play a role to stop and kill the pest before reaching risk zones in the northern part adjacent to the Mediterranean Sea of Mediterranean climate and/or irrigated agriculture area adjacent to the Atlantic Ocean, that can met the conditions for the survival and development of FAW [29,46]. Thus, FAW monitoring should be strengthened in these regions face to the Canary Islands where are the FAW host plants such as corn and favorable climatic conditions.

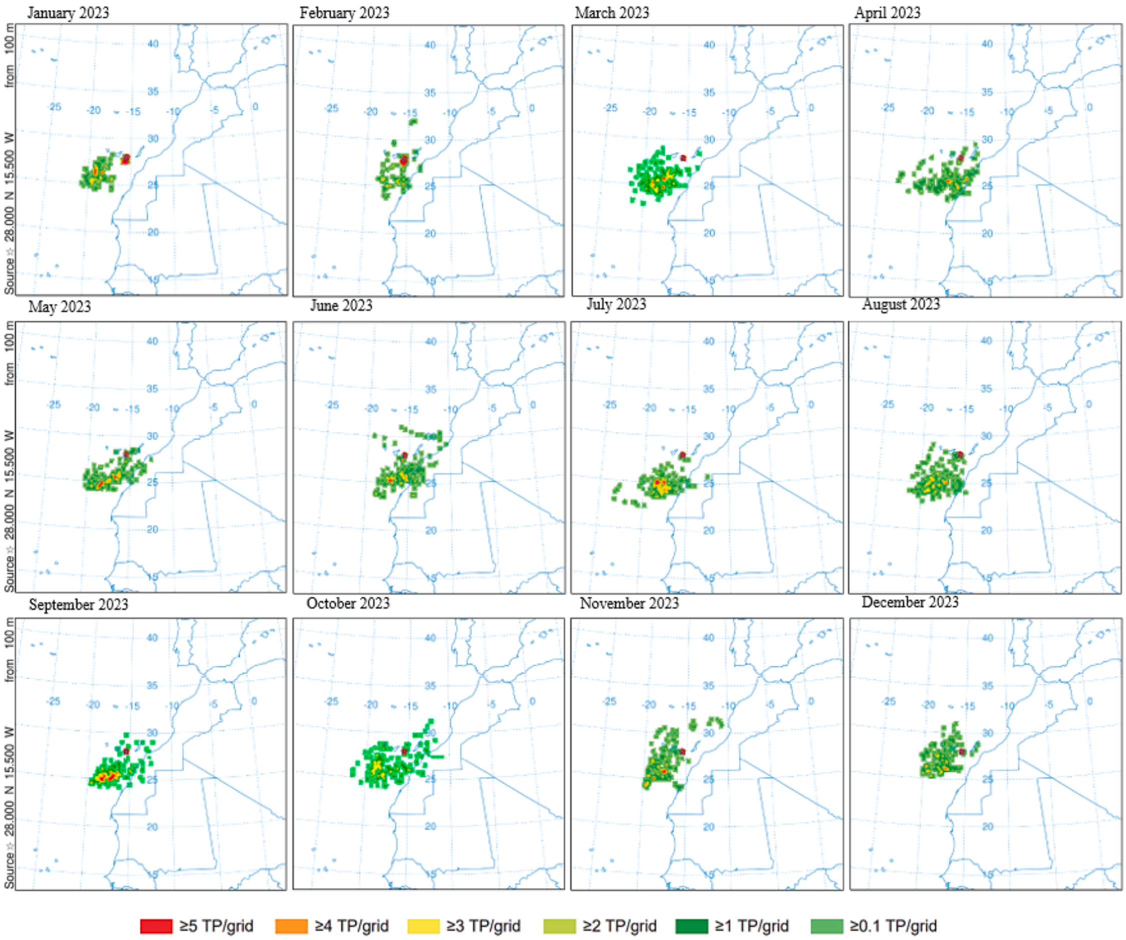

Fig. 8. Monthly distribution of FAW terminal points (TPs) from forward trajectories starting at Canary Island at 1500 m height in 2023. The color scale indicates the frequency of valid terminal points (TPs) per 0.25° × 0.25° grid cell, averaged over the month. Frequencies may include decimal values as they represent monthly averages across 6 trajectories per day (~180 per month). A red point marks the trajectory starting location.

Conclusion

This study assessed the migration risk of the fall armyworm, *Spodoptera frugiperda*, into Morocco using forward trajectory modeling from four selected West African countries. The results indicate that, while FAW presence is confirmed in regions adjacent to Morocco, the modeled trajectories showed only a low probability of the pest reaching Moroccan territory under current climatic and geographic conditions. Most trajectories terminated in southern Mauritania, northern Senegal, or over the Atlantic Ocean, with few reaching Morocco directly. The findings suggest that the natural spread of FAW into Morocco is limited by arid southern zones lacking host plants and by unfavorable wind patterns for northward migration. However, given the pest's flight capacity, potential for human-assisted movement, and changing climate, the risk cannot be entirely excluded. Surveillance efforts should therefore continue, particularly in northern and coastal regions with suitable crops and climates, such as areas facing the Canary Islands. Future studies should also consider potential invasion pathways from the north, including southern Europe, especially given the agricultural importance of northern Morocco. Early detection through pheromone trapping and field monitoring remains essential to prevent possible establishment of FAW populations in Morocco. The findings of this study provide valuable guidance for agricultural decision-makers and plant protection authorities in Morocco and the surrounding region. By identifying areas with low but potential FAW incursion risk, the results can be used to inform the strategic placement of pheromone traps, the design of targeted surveillance programs, and the allocation of resources for early warning systems. Furthermore, the modeling framework developed in this study can be integrated into national pest surveillance programs to improve forecasts of future migration events and to support quarantine and management policies under changing climatic conditions.

CRediT authorship contribution statement

Khalid Khfif: Conceptualization, Investigation, Formal analysis, Funding acquisition, Writing – original draft. **Awa Ndiyae:** Data curation, Writing – review & editing. **Kofi Frimpong-Anin:** Data curation, Writing – review & editing. **Assienin Hauverset N'guessan:** Data curation, Writing – review & editing. **Timothy Oluwafemi Ajiboye:** Data curation, Writing – review & editing. **Akira Otuka:** Methodology, Software, Formal analysis, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research conducted was funded by the National Institute for Agricultural Research (INRA-Morocco) and the grant of KAFACI/RDA, Republic of Korea.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sciaf.2025.e03158.

References

[1] R. Day, P. Abrahams, M. Bateman, T. Beale, V. Clottey, M. Cock, Support project for the implementation of a sustainable management strategy for the fall armyworm in Burkina Faso. Terminal Report, FAO, Roma, (2017) 6 p.
[2] 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, Afr. Entomol. 26 (2) (2018) 286–300, https://doi.org/10.4001/003.026.0286.
[3] B. Prasana, E. Joseph, E. Huesing, E. Regina, M. Virginia, E. Peschke, Fall Armyworm in Africa: a guide for integrated pest management. CIMMYT, Ciudad de México (2018).
[4] I. Rwomushana, M. Bateman, T. Beale, P. Beseh, K. Cameron, M. Chiluba, V. Clottey, T. Davis, R. Day, R. Early, J. Godwin, P. Gonzalez-Moreno, M. Kansiime, M. Kenis, F. Makale, I. Mugambi, S. Murphy, W. Nunda, N. Phiri, C. Pratt, J. Tambo, FAW impact and implication for Africa Evidence Note Update, CABI (2018).
[5] H. De Groote, S.C. Kimenju, B. Munyua, S. Palmas, M. Kassie, A. Bruce, Spread and impact of fall armyworm (*Spodoptera frugiperda* J.E. Smith) in maize production areas of Kenya, Agric. Ecosyst. Environ. 292 (2020) 106804, https://doi.org/10.1016/j.agee.2019.106804.
[6] Z. Abro, E. Kimathi, H. De Groote, T. Tefera, S. Sevgan, S. Niassy, M. Kassie, Socioeconomic and health impacts of fall armyworm in Ethiopia, PLoS. One 16 (11) (2021) e0257736, https://doi.org/10.1371/journal.pone.0257736.
[7] K. Overton, J.L. Maino, R. Day, P.A. Umina, B. Bett, D. Carnovale, S. Ekesi, R. Meagher, O.L. Reynolds, Global crop impacts, yield losses and action thresholds for fall armyworm (*Spodoptera frugiperda*): a review, Crop. Prot. 145 (2021) 105641, https://doi.org/10.1016/j.cropro.2021.105641.
[8] R.A. Guimapi, S. Niassy, B.T. Mudereri, E.M. Abdel-Rahman, G.T. Tepa-Yotto, S. Subramanian, S.A. Mohamed, K.H. Thunes, E. Kimathi, K.M. Agboka, C.J. R. Tamo, B. Hadi, M. Elkahky, M.-G. Saethre, Y. Belayneh, S. Ekesi, S. Kelemu, H.E.Z. Tonnang, Harnessing data science to improve integrated management of invasive pest species across Africa: an application to fall armyworm (*Spodoptera frugiperda*) (J.E. Smith) (Lepidoptera: noctuidae), Glob. Ecol. Conserv. 35 (2022) e0205, https://doi.org/10.1016/j.gecco.2022.e02056.
[9] K. Aleem, M. Imran, S. Bashir, A. Pernia, M. Manzoor, M.S. Anwar, M. Akbar, I. Munawar, Integrated pest management strategies for invasive fall armyworm, Agrobiol. Records 12 (2023) 53–59, https://doi.org/10.47278/journal.abr/2023.014.
[10] J.K. Westbrook, A.N. Sparks, The role of atmospheric transport in the economic fall armyworm (Lepidoptera: noctuidae) infestations in the southeastern united states in 1977, Fla. Entomol. 69 (1986) 492, https://doi.org/10.2307/3495382.
[11] J. Ma, Y.P. Wang, M.F. Wu, B.F. Gao, J. Liu, G.S. Lee, A. Otuka, G. Hu, High risk of the fall armyworm invading Japan and the Korean Peninsula via overseas migration, J. Appl. Entomol. 00 (2019) 1–10, https://doi.org/10.1111/jen.12679.
[12] H. Chen, Y. Wang, L. Huang, C.F. Xu, J.H. Li, F.Y. Wang, et al., Flight capability and the low temperature threshold of a Chinese field population of the fall armyworm *Spodoptera frugiperda*, Insects 13 (2022) 422, https://doi.org/10.3390/insects13050422.
[13] A. Otuka, T. Niiyama, X. Jiang, Possible source and migration pathway for early-summer immigrants of the oriental armyworm, *Mythimna separata*, arriving in northern Japan, J. Integr. Agric. 22 (11) (2023) 3474–3488, https://doi.org/10.1016/j.jia.2023.06.001.
[14] J.T. Hardke, G.M. Lorenz, B.R. Leonard, Fall armyworm (Lepidoptera: noctuidae) ecology in southeastern cotton, J. Integrated. Pest Manag. 6 (2015), https://doi.org/10.1093/jipm/pmv009, 10–10.
[15] 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 (2016) e0165632, https://doi.org/10.1371/journal.pone.0165632.
[16] M.H. Otim, W.T. Tay, T.K. Walsh, D. Kanyesigye, S. Adumo, J. Abongosi, et al., Detection of sister-species in invasive populations of the fall armyworm *spodoptera frugiperda* (Lepidoptera: noctuidae) from Uganda, PLoS. One 13 (2018) e0194571, https://doi.org/10.1371/journal.pone.0194571.
[17] B. Sisay, J. Simiyu, E. Mendesil, P. Likhayo, G. Ayalew, S. Mohamed, et al., Fall armyworm, *spodoptera frugiperda* infestations in East Africa: assessment of damage and parasitism, Insects. 10 (2019) 195, https://doi.org/10.3390/insects10070195.
[18] N. Elibariki, A.S.R. Bajracharya, B. Bhat, T. Tefera, J.L. Mottern, G. Evans, et al., Candidates for augmentative biological control of *spodoptera frugiperda* (J e smith) in Kenya, Tanzania and Nepal, Indian J. Entomol. 82 (2020) 606–608, https://doi.org/10.5958/0974-8172.2020.00088.7.
[19] P.M. Matova, C.N. Kamutando, C. Magorokosho, D. Kutywayo, F. Gutsa, M. Labuschagne, Fall-armyworm invasion, control practices and resistance breeding in Sub-Saharan Africa, Crop. Sci. 60 (2020) 2951–2970, https://doi.org/10.1002/csc2.20317.
[20] FAO, Briefing note on fall armyworm (FAW) in Africa, (2018) 7p https://openknowledge.fao.org/server/api/core/bitstreams/fb914387-1559-4b90-ba3f-a1c668fc88e1/content.
[21] W. Gamil, Fall armyworm *spodoptera frugiperda* (J. e. smith) (Lepidoptera: noctuidae) biological aspects as a new alien invasive pest in Egypt, Egyptian. Acad. J. Biol. Sci. A. Entomol. 13 (2020) 189–196, https://doi.org/10.21608/eajbsa.2020.110344.
[22] EPPO, First report of *Spodoptera frugiperda* in Mauritania, (2020), https://gd.eppo.int/reporting/article-6821.
[23] A. Vives Moreno, J. Gastón, Five new species for the fauna of Spain and other interesting lepidopterological information for Spain and Sudan (Insecta: lepidoptera), SHILAP Revista lepidopterología 48 (192) (2020) 717–731.
[24] EPPO, First report of *Spodoptera frugiperda* in the Canary Islands, Spain, (2021), https://gd.eppo.int/reporting/article-6992.
[25] S. Pehlivan, E. Atakan, First record of the fall armyworm, *spodoptera frugiperda* (J.E. Smith, 1797) (Lepidoptera: noctuidae) in Türkiye, Çukurova J. Agric. Food Sci. 37 (2) (2022) 139–145, https://doi.org/10.36846/CJAFS.2022.82.

[26] I. Lytra, V. Evangelou, S. Antonatos, I. Georgopoulou, E. Tselou, D. Dimopoulou, C. Arampatzis, P. Milonas, D.P. Papachristos, First data on the occurrence and population dynamics of the fall armyworm *Spodoptera frugiperda* (Lepidoptera: noctuidae) in Greece, Bull. OEPP/EPPO Bull. 54 (2) (2024) 217–223, https://doi.org/10.1111/epp.13021.

[27] M. Cean, A. Taddei, R.A. Gottsberger, H. Reisenzein, E.I.V. Georgescu, First report of the fall armyworm *spodoptera frugiperda* (J.E. Smith, 1797) in Romania, Bull. OEPP/EPPO Bull. 54 (2) (2024) 212–216, https://doi.org/10.1111/epp.13017.

[28] P. Abrahams, M. Bateman, T. Beale, V. Clotty, M. Cock, et al., Fall Armyworm: Impacts and Implications for Africa, Evidence Note. 2 (2017) 144.

[29] J. Wang, Y. Huang, L. Huang, Y. Dong, W. Huang, H. Ma, H. Zhang, X. Zhang, X. Chen, Y. Xu, Migration risk of fall armyworm (*Spodoptera frugiperda*) from North Africa to Southern Europe, Front. Plant Sci. 14 (2023) 1141470, https://doi.org/10.3389/fpls.2023.1141470.

[30] L. Makra, K. Bodnár, A. Fülöp, S. Orosz, A. SzénásI, Z. Csépe, G. Jenser, G. Tusnády, D. Magyar, The first record of subtropical insects (Thysanoptera) in central Europe: long-distance transport of airborne thrips, applying three-dimensional backward trajectories, Agric. For. Entomol. (2017) 1–26, https://doi.org/10.1111/afe.12260.

[31] D.L. Huestis, A. Dao, M. Diallo, Z.L. Sanogo, D. Samake, A.S. Yaro, et al., Windborne long-distance migration of malaria mosquitoes in the sahel, Nature 574 (2019) 404–408, https://doi.org/10.1038/s41586-019-1622-4.

[32] R.N. Nagoshi, S. Fleischer, R.L. Meagher, M. Hay-Roe, A. Khan, et al., Correction: fall armyworm migration across the Lesser Antilles and the potential for genetic exchanges between North and South American populations, PLoS. One 12 (3) (2017) e0175076, https://doi.org/10.1371/journal.pone.0175076.

[33] J. Westbrook, S. Fleischer, S. Jairam, R. Meagher, R. Nagoshi, Multigenerational migration of fall armyworm, a pest insect, Ecosphere 10 (2019) e02919, https://doi.org/10.1002/ecs2.2919.

[34] R.R. Draxler, G.D. Hess, Description of the HYSPLIT_4 Modeling System. NOAA Tech. Memo. ERL ARL-224. NOAA Air Resources Laboratory, Silver Spring, MD, (1997) 1–24.

[35] R.R. Draxler, G.D. Hess, An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition, Aust. Meteorol. Mag. 47 (1998) 295–308.

[36] A.F. Stein, R.R. Draxler, G.D. Rolph, B.J.B. Stunder, M.D. Cohen, F. Ngan, NOAA's HYSPLIT atmospheric transport and dispersion modeling system, Bull. Am. Meteorol. Soc. 96 (2015) 2059–2077.

[37] J.W. Chapman, R.L. Nesbit, L.E. Burgin, D.R. Reynolds, A.D. Smith, D.R. Middleton, et al., Flight orientation behaviors promote optimal migration trajectories in highflying insects, Science 1979 327 (2010) 682–685, https://doi.org/10.1126/science.1182990.

[38] F.Y. Wang, F. Yang, M.H. Lu, S.Y. Luo, B.P. Zhai, K.S. Lim, et al., Determining the migration duration of rice leaf folder (*Cnaphalocrocis medinalis* (Guenée)) moths using a trajectory analytical approach, Sci. Rep. 7 (2017) 39853, https://doi.org/10.1038/srep39853.

[39] M. Minter, A. Pearson, K.S. Lim, K. Wilson, J.W. Chapman, C.M. Jones, The tethered flight technique as a tool for studying life-history strategies associated with migration in insects: tethered flight for studying insect movement, Ecol. Entomol. 43 (2018) 397–411, https://doi.org/10.1111/een.12521.

[40] ARL (Air Resources Laboratory, USA), HYSPLIT User's Guide, National Oceanic and Atmospheric Administration, Boulder, CO, 2022, pp. 1–315.

[41] Google Earth, Available on: https://earth.google.com/web/@25.09269768,-10.46178505,-2726.87718221a,5360629.88568127d,35y,0h,0t,0r/data=CgRCAggBQgIIAEoNCP________wEQAA, 2024.

[42] B.R. Ahissou, W.M. Sawadogo, F. Sankara, Y. Brostaux, A.H. Bokonon-Ganta, I. Somda, F. Verheggen, Annual dynamics of fall armyworm populations in West Africa and biology in different host plants, Sci. Afr. 16 (2022), https://doi.org/10.1016/j.sciaf.2022.e01227.

[43] FAO, (2024), Global Action for fall armyworm control. Available on: https://www.fao.org/fall-armyworm/monitoring-tools/faw-map/en/.

[44] Q.L. Wu, X.J. Shen, L.M. He, Y.Y. Jiang, J. Liu, G. Hu, K.M. Wu, Windborne migration routes of newly-emerged fall armyworm from Qinling Mountains–Huaihe River region, China. J. Integr. Agric. 20 (3) (2021) 694–706, https://doi.org/10.1016/S2095-3119(20)63207-5.

[45] W.T. Tay, R.V. Rane, A. Padovan, T.K. Walsh, S. Elfekih, S. Downes, K. Nam, E. d'Alençon, J. Zhang, Y. Wu, N. Nègre, D. Kunz, D.J. Kriticos, C. Czepak, M. H. Otim, K.H.J. Gordon, Global population genomic signature of *Spodoptera frugiperda* (fall armyworm) supports complex introduction events across the Old World, Commun. Biol. 5 (1) (2022). Article 1.

[46] H. Du Plessis, J. Van Den Berg, N. Ota, D.J. Kriticos, *Spodoptera frugiperda*. CSIRO-InSTePP Pest Geography, Canberra, (2018), Available at: https://www.researchgate.net/publication/327423712.