J. Entomol. Res. Soc., 27(1): 163-174, 2025
Doi: 10.51963/jers.v27i1.2786

Research Article
Online ISSN:2651-3579

Potential Alterations in the Spread of the Honey Bee Pest, *Senotainia tricuspis*, Across the Mediterranean Region and Africa in Response to Shifting Climatic Conditions

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ABSTRACT

There are several parasitic flies capable of infecting honey bees, resulting in significant economic losses. One such fly is *Senotainia tricuspis*, which has been documented in several countries within the Mediterranean region. The potential for these flies to expand their range into more areas across Europe and Africa, particularly in response to climate change over the coming years, remains unstudied. In this study, maximum entropy modeling using Maxent and six temperature variables were employed to address this gap. The model exhibited strong performance, as indicated by output parameters, with both test and training data showing an area under the curve close to 1. The current distribution closely mirrored the actual prevalence of *S. tricuspis* in the Mediterranean region. Future prevalence projections for 2050 and 2070, based on two Shared Socio-economic Pathways (SSP 126 and SSP 585), illustrated a high likelihood of *S. tricuspis* occurrence in southern Europe, North Africa spanning from Egypt to Morocco, and the Levant. However, the study did not find support for the wide invasion of Central and Southern African countries by this fly, except for specific areas in Madagascar and South parts of Africa. The study delved into the roles of the environmental variables in influencing *S. tricuspis* prevalence and discussed potential implications for beekeeping.

Keywords: Modeling, pest, *S. tricuspis*, apiculture, parasites.

Abou-Shaara, H. F. & Al-Khalaf, A. A. (2025). Potential alterations in the spread of the honey bee pest, *Senotainia tricuspis,* across the Mediterranean region and Africa in response to shifting climatic conditions. *Journal of the Entomological Research Society*, 27(1), 163-174.

Received: December 31, 2024 *Accepted: February 18, 2025*

INTRODUCTION

The pest *Senotainia tricuspis*, a Diptera of the family Sarcophagidae, poses a threat to honey bee, *Apis mellifera* (Morse & Flottum, 1997; Felicioli, Franceschini, & Pinzauti, 2000). This particular fly has long been recognized as an endoparasitoid of honey bees (Simintzis & Fiasson, 1950). However, information regarding its prevalence remains confined to select countries within the Mediterranean region. Notably, this species has been observed in several European nations, such as Spain (Bermejo, Megías, & Fernández, 1996), Italy (Pinzauti & Santini, 1995; Felicioli, Franceschini, & Pinzauti, 2000; Piazza & Marinelli, 2000; Bedini, Pinzauti, & Felicioli, 2006; Bedini et al., 2023), Turkey (Kara & Pape, 2002), Portugal (Rocha & Mira Delgado, 1986; Pires, Cadavez, & Valério, 2011), as well as various countries in North Africa and the Middle East, including Egypt (Ibrahim, 1980; Nour, 1993), Syria (Hatoom, 1996), Jordan (Al-Chzawi, Zaitoun, & Shannag, 2009), and Algeria (Haddad et al., 2015). Regrettably, the resemblance of this parasitoid to other Sarcophagidae flies (Ferrazzi & Dutto, 2014) can lead to misidentifications. Recently, a swift molecular technique has been devised to aid in the discernment of parasitoid flies targeting honey bees (Rossi et al., 2024).

The parasitoid *S. tricuspis* exhibits activity throughout the year, yet diapause occurs in larvae/pupae during specific periods, notably from autumn to spring (Bailey & Ball, 1991). Female *S. tricuspis* targets forager bees, depositing 1st instar larvae on the thoraxes of bees, which then penetrate the bee's body to feed on hemolymph and wing muscles (Bedini, Pinzauti, & Felicioli, 2006). The aggressive behavior of *S. tricuspis* towards honey bees has been well-documented, involving pursuits, aggression, capturing bees, and parasitization (Bedini et al., 2023). Infected bees can survive for a brief period, typically up to 4 days, after which 3rd instar larvae pupate in the soil. Consequently, the low survival rate of infected bees is expected to result in significant economic losses. Notably, cannibalism may occur among *S. tricuspis* larvae (Pinzauti & Santini, 1995). The substantial harm caused by this fly is termed senotainiosis. These flies can also aid in the dissemination of honey bee pathogens (Rossi et al., 2024), further compromising bee colony health.

One major challenge facing beekeeping is the impact of climate change (Neumann & Straub, 2023). It is anticipated that the geographic distribution of honey bee pests will undergo changes in the foreseeable future due to climatic shifts (Le Conte & Navajas, 2008; Abou-Shaara, 2016; Neumann & Straub, 2023), particularly evident alterations in air temperatures (Le Conte & Navajas, 2008; Yoruk & Sahinler, 2013; Abou-Shaara, 2016). Thus, temperature parameters linked to the Shared Socio-economic Pathways (SSPs) can be employed to forecast shifts in the spread of bee pests (Abou-Shaara & Darwish, 2021; Abou-Shaara & Al-Khalaf, 2022), in conjunction with modeling tools (Guisan & Thuiller, 2005; Wei et al., 2018; Abou-Shaara, 2024). SSPs are currently utilized for prognostic purposes in alignment with the Intergovernmental Panel on Climate Change (IPCC) guidelines. This study focused on modeling the existing and future prevalence of *S. tricuspis* in the Mediterranean region and Africa using six temperature variables, following the exclusion of environmental variables displaying anomalous data patterns (Escobar et al., 2014; Samy et al., 2016; Alkishe, Peterson, & Samy, 2017; Abou-Shaara, 2024). The findings underscore the impact of climate change on *S. tricuspis* for the timeframes of 2050 and 2070. Notably, this study is the first to elucidate the impact of environmental variables on the spread of *S. tricuspis* throughout the Mediterranean region and Africa under changing climate conditions.

MATERIALS AND METHODS

Collection of occurrence records

The presence of *S. tricuspis* has been verified in several countries situated in the Mediterranean Sea region and the Middle East, notably Italy, Egypt, Algeria, and Jordan. For the analysis, each country contributed 15 records, with the exception of Italy, which provided 30 records, totaling 75 records. The additional 15 records from Italy were specifically attributed to Sardinia Island. These data points were identified in accordance with the research conducted by Haddad et al. (2015). To validate their accuracy and presence in the specified areas, all records were cross-checked using Google Earth. Given the scarcity of occurrence records from alternative sources, the records utilized in this study are sufficient for the study's purpose.

Environmental variables

This study utilized specific variables (Table 1) as outlined in previous research (Abou-Shaara & Darwish, 2021), which significantly influence the prevalence of parasitic honey bee pests. These variables were sourced from WorldClim v2.1 at a spatial resolution of approximately 5 km². Projected values for these variables spanning the periods 2041 to 2060 (with 2050 as the midpoint) and 2061 to 2080 (with 2070 as the midpoint) were derived from the climate model developed by the National Centre for Meteorological Research (CNRM-CM6-1) (Eyring et al., 2016). Two Shared Socio-economic Pathways (SSP126 and SSP585) were utilized for each of the designated time points (2050 and 2070) as part of the analysis (Abou-Shaara & Al-Khalaf, 2022).

Table 1. Temperature variables used in the modeling.

Number	Variable	Abbreviation
1	Annual mean temperature (ºC)	Bio1
2	Mean diurnal range (ºC) (=Mean of max monthly temp - min monthly temp)	Bio2
3	Maximum temperature of warmest month (ºC)	Bio5
4	Minimum temperature of coldest month (ºC)	Bio6
5	Mean temperature of warmest quarter (ºC)	Bio10
6	Mean temperature of coldest quarter (ºC)	Bio11

Maximum entropy modeling

The analysis was conducted utilizing maximum entropy modeling in Maxent version 3.4.1 (Phillips, Dudík, & Schapire, 2017). Initially, temperature datasets (averaged from 1970 to 2000) were employed to delineate the current distribution of *S. tricuspis* (Abou-Shaara & Al-Khalaf, 2022; Abou-Shaara, 2024). Subsequently, temperature datasets for 2050 and 2070 were utilized to forecast the future distribution of *S. tricuspis* in the Mediterranean Sea region and Africa. Specific settings for the model configuration are detailed in Table 2. The outcomes were visualized through maps with a legend categorized into five classes using ArcGIS 10.5 (Table 2).

Table 2. Parameters employed in conducting the Maximum Entropy modeling process.

Settings	Value
Records	57 records used for training and 18 for testing
Background and presence points	10057 points to determine the Maxent distribution
Linear/quadratic/product	0.173
Categorical	0.250
Threshold	1.430
Hinge	0.500
Output format	Cumulative
Suitability classes	Very low (0-0.01), Low (0.01-1), Moderate (1-20), Suitable (20-50), and Highly Suitable (50-100)

Contribution percentages and model performance

The model outputs provided the percentage contribution of each temperature variable within the model. These contributions were analyzed and discussed to delineate the optimal thresholds of these variables for the fly's distribution as depicted in the generated maps. Additionally, the Maxent program computed various parameters such as the area under the curve (AUC), omission/commission rates, receiver operating characteristic, and jackknife test values for the temperature variables employed. These metrics were leveraged to assess the efficacy of the Maximum Entropy model (Abou-Shaara & Al-Khalaf, 2022; Abou-Shaara, 2024).

RESULTS

Distribution under existing environmental conditions

The analysis revealed the current temperature suitability for *S. tricuspis* across multiple countries in the Mediterranean region, as illustrated in Fig. 1. Coastal areas in North Africa exhibited high suitability for this fly, while Italy, Spain, France, and Portugal demonstrated notably higher suitability compared to other European regions for the presence of *S. tricuspis*. Conversely, the deserts of North Africa and mountainous terrains in Europe exhibited lower suitability for this species, reflecting the extreme temperature conditions—ranging from very high to very low—throughout the year. Moreover, Sub-Saharan Africa demonstrated low to moderate suitability for *S. tricuspis* under present conditions.

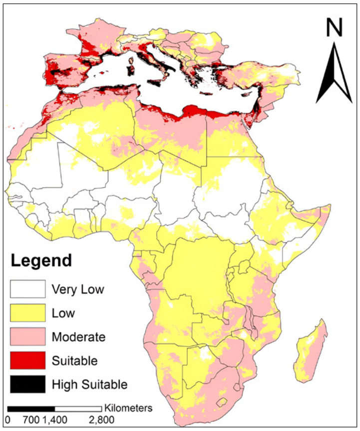

Figure 1. The current presence of *Senotainia tricuspis* in the Mediterranean Region and its potential spread to other African regions under existing environmental conditions.

Future distribution during 2050

The two maps depicting future conditions for 2050 under SSP 126 and SSP 585 reaffirmed the presence of *S. tricuspis* in the coastal areas of North Africa and certain southern European countries, as depicted in Fig. 2. However, the maps based on these scenarios did not indicate widespread invasion and establishment of *S. tricuspis* in Africa. Predominantly, lower distribution values were noted in countries near the equator. It is evident that regions with elevated temperatures in Africa will not be conducive for the proliferation of *S. tricuspis*. Additionally, certain European regions, particularly those characterized by very low temperatures and mountainous terrain, will not be suitable habitats for *S. tricuspis* under changing climatic conditions. Southern regions of Africa and specific areas in Madagascar exhibited moderate suitability for the presence of this pest. Consequently, the occurrence of *S. tricuspis* in these particular regions may transpire under specific conditions, such as the accidental introduction of *S. tricuspis* to these areas.

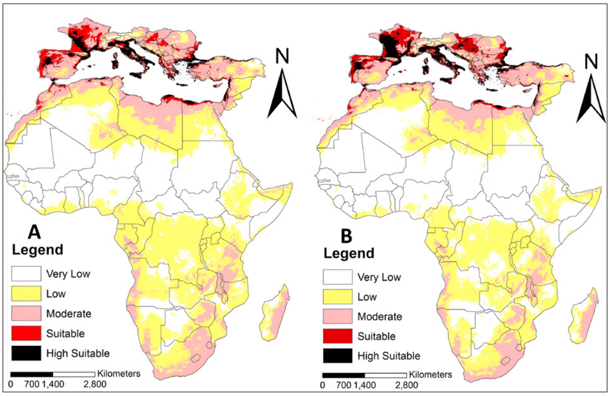

Figure 2. Projected distribution of *Senotainia tricuspis* in the Mediterranean Region and Africa by 2050: A) Lower boundary of SSP 126 and B) upper boundary of SSP 585.

Future distribution during 2070

The two maps illustrating future conditions for 2070 indicate a significant expansion of *S. tricuspis* in specific regions of North Africa and Europe, as depicted in Fig. 3. As in the 2050 projections, the widespread invasion and establishment of *S. tricuspis* in central and southern African countries are not anticipated, with the exception of coastal areas in South Africa and Madagascar. Both the 2050 and 2070 maps suggest a notable increase in the invasion and establishment of *S. tricuspis* in various regions of southern European countries compared to the current scenario depicted in Fig. 1.

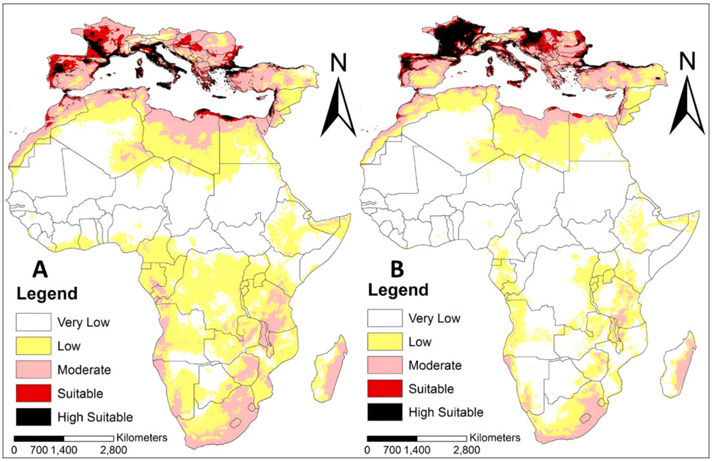

Figure 3. Projected distribution of Senotainia tricuspis in the Mediterranean Region and Africa by 2070: A) Lower bound of SSP 126 and B) upper bound of SSP 585.

Contribution percentages and model performance

The model exhibited the greatest influence from Bio 11, succeeded by Bio 2, Bio 5, and finally Bio 10, as outlined in Table 3. Conversely, Bio 1 and Bio 6 made the smallest contributions, totaling 2.2%. Bio 11 alone accounted for 56.1% of the overall contribution, whereas the remaining variables collectively represented 43.9%. Table 3 and Figure 4 demonstrate the response curves of the top four contributing variables. Optimal temperatures for Bio 11 fell within the 5 to 10°C range, indicating unsuitability for extreme low and high temperatures. For Bio 2, Bio 5, and Bio 10, ideal ranges were 8-9°C, 33-34°C, and 21-24°C, respectively.

Table 3. Contribution of temperature variables in the model.

Variable	Contribution percentages
Annual mean temperature (Bio1)	2.1
Mean diurnal range (Bio2)	27.1
Maximum temperature of warmest month (Bio5)	7.5
Minimum temperature of coldest month (Bio6)	0.1
Mean temperature of warmest quarter (Bio10)	7.1
Mean temperature of coldest quarter (Bio11)	56.1

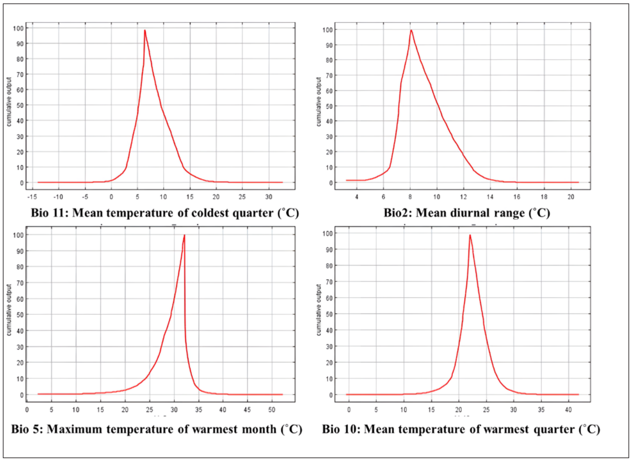

Figure 4. Graphs depicting the response curve of the top four temperature variables with the greatest contribution percentages in the model.

The mean temperature of the coldest quarter (Bio11) exhibited the greatest gain when utilized independently, indicating the richness of its standalone information (Fig. 5A). Conversely, the exclusion of the maximum temperature of the warmest month (Bio5) resulted in the most substantial decrease in gain, highlighting the unique information it contributes compared to the other temperature variables. The area under the curve (AUC) for all variables surpassed 0.78, as depicted in Fig. 5B.

Values exceeding 0.6 in fraction indicated a convergence between the omission lines of training and test samples with the predicted omissions, as illustrated in Fig. 6A. The receiver operating characteristic for *S. tricuspis* (Fig. 6B) displayed the computed area under the curve (AUC) values, which stood at 0.982 for the test data and 0.983 for the training data.

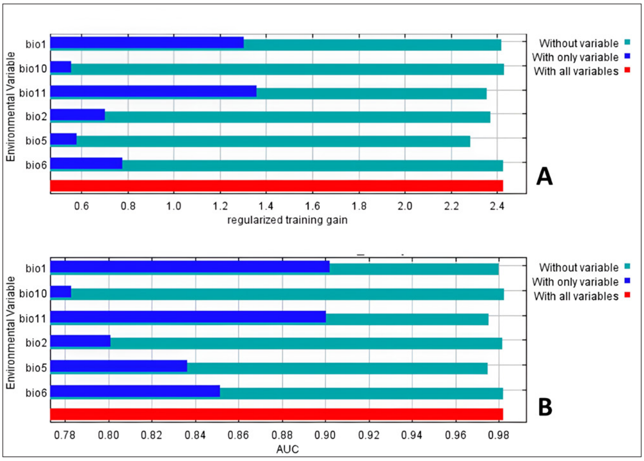

Figure 5. A) The jackknife test results for regularized training gain, B) the area under the curve on test data.

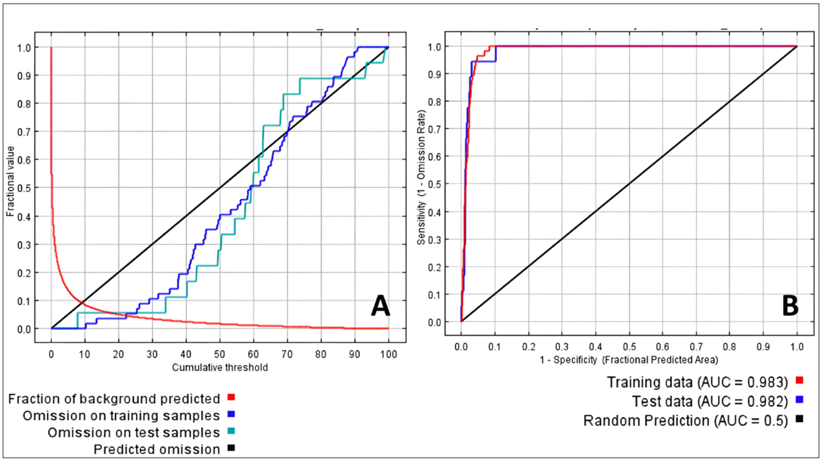

Figure 6. Analysis of omission/commission for *Senotainia tricuspis*. A) Omission and predicting area, B) the receiver operating characteristic.

DISCUSSION

The current distribution pattern closely mirrored the actual prevalence of this fly in the Mediterranean region, encompassing countries from Egypt to Morocco and the Levant, as supported by previous studies (Hatoom, 1996; Al-Chzawi, Zaitoun, & Shannag, 2009; Haddad et al., 2015), along with Southern Europe (Bermejo, Megías, & Fernández, 1996; Kara & Pape, 2002; Bedini, Pinzauti, & Felicioli, 2006; Pires, Cadavez, & Valério, 2011). The research highlighted the potential prevalence of the fly in North Africa, spanning from Egypt to Morocco, with limited records available only from Egypt and Algeria, and scarce investigations conducted in Libya, Tunisia, and Morocco. Certain areas exhibited a higher preference for the fly's prevalence than others, with coastal regions demonstrating greater prevalence compared to deserts and mountainous terrains, indicating the fly's inclination towards moist and temperate conditions. Despite this, precise data on the occurrence of *S. tricuspis* remain sparse. Therefore, further investigations are imperative, especially given that model projections imply a heightened prevalence of *S. tricuspis* in the Mediterranean region under present climatic conditions.

The robust prevalence of *S. tricuspis* in the Mediterranean region is corroborated by forthcoming maps for 2050 and 2070, referencing SSP 126 and SSP 585. These projections imply that forthcoming climatic conditions will continue to support this fly's prevalence without diminishing it. Areas proximate to the Mediterranean Sea are shown to be more conducive for the proliferation of this species compared to desert or mountainous regions. In line with this, a study by Haddad et al. (2015) indicates a preference for wetter conditions over arid ones. Additionally, southern Spain emerges as highly suitable for this fly, with minimal infestation of bee colonies, as noted by Bermejo, Megías, & Fernández (1996).

Interestingly, areas characterized by extremely high temperatures (near the equator) and those with the coldest climates (such as mountainous regions) exhibited the least potential for *S. tricuspis* prevalence. As a result, regions in Africa beyond North Africa are unlikely to face invasion by this fly. The introduction of *S. tricuspis* is only anticipated through accidental means, potentially leading to its presence in specific areas in Madagascar and South parts of Africa. Accidental introductions of honey bee pests and pathogens could occur through migratory beekeeping and the exchange of bee packages and beekeeping equipment, as highlighted by Neumann and Elzen (2004), Mutinelli (2011), and Gordon, Bresolin-Schott, & East (2014). As an example, the Asian hornet, *Vespa velutina*, and the facultative parasitoid *Megaselia scalaris* have been expected to be introduced to new regions through accidental introductions (Abou-Shaara and Darwish, 2021; Abou-Shaara and Al-Khalaf, 2022).

None of the maps indicated the likelihood of this fly invading Africa except for coastal regions. Minor discrepancies were observed between the 2050 and 2070 maps. Notably, Italy, Spain, Portugal, Greece, and France are anticipated to face significant infestations by this fly, underscoring the need for screening studies in these nations. An infestation by this fly can result in substantial damage to bee colonies, particularly due to the female's ability to deposit up to 700 larvae in forager bees (Bedini et al., 2006). This high number of parasitic larvae can diminish adult bee survival rates, leading to a decline in forager bee populations and subsequent colony losses. An older study by Mathis (1975) drew a correlation between bee colony disappearances and infestations caused by this fly. It is essential to develop methods for controlling this fly, given the limited availability of effective control strategies. One potential approach involves using chromotropic traps coated with glue, positioned above hive outer covers (Piazza & Marinelli, 2000). Perhaps utilizing organic materials within colonies to combat parasitic pests, such as the application of oxalic acid (Abou-Shaara, Staron, & Cermakova, 2017), could aid in reducing infestations, but further studies are needed. Additionally, employing biological control techniques to regulate this fly's populations is crucial, mirroring strategies used for managing other bee pests (Abou-Shaara & Staron, 2019).

The model highlighted the significant influence of the variable "Mean temperature of coldest quarter," followed by "Mean diurnal range". Notably, all variables indicated a range of suitability between 5°C and 34°C for *S. tricuspis* prevalence. This range aligns well with the observed occurrences of this fly, particularly as previous studies noted its highest prevalence in Spain during July (summer) (Bermejo, Megías, & Fernández, 1996), and in Portugal during July and September (summer and early autumn) (Pires, Cadavez, & Valério, 2011). Contrarily, the variable "Minimum temperature of coldest month" exhibited the least impact in the model, with a contribution percentage of 0.1. This low contribution could be attributed to the fly's diapause period during periods of low air temperatures, as discussed in studies by Bailey & Ball (1991) and Piazza & Marinelli (2000). Consequently, the model's reduced emphasis on this specific temperature variable indicates a high level of result accuracy, suggesting that the coldest months are not pivotal in the fly's prevalence. Furthermore, research in Italy identified specific areas conducive for the pupation and overwintering of these flies, particularly favoring sunny locations with sandy soil (Piazza & Marinelli, 2000). This finding underscores the fly's tendency to avoid colder conditions in favor of moderate temperature environments.

The model exhibited strong performance, with omission rates on both training and test samples closely aligning with predicted values, especially for fractional values exceeding 0.6. Additionally, the areas under the curve were notably high, deviating from 1 by only 0.018 for test data and 0.017 for training data. These results suggest that the model performed exceptionally well, as supported by studies conducted by Mulieri & Patitucci (2019), Hosni et al. (2020), Abou-Shaara & Al-Khalaf (2022), and Abou-Shaara (2024).

CONCLUSION

The findings of the model indicate a probable expansion and establishment of *S. tricuspis* in Mediterranean countries in the near future. Coastal regions spanning from Egypt to Morocco in North Africa and various Southern European countries are projected to be highly conducive for *S. tricuspis*. Consequently, beekeepers should prioritize research on apiary infestation rates by *S. tricuspis* and the development of control strategies. The potential economic repercussions stemming from the proliferation of *S. tricuspis* must also be factored in. The study suggests that the spread of *S. tricuspis* towards Central and South Africa is unlikely, except for specific areas in Madagascar and southern parts of Africa where accidental introductions may occur. The inclination of *S. tricuspis* towards coastal regions and cooler temperatures implies a higher prevalence under moderate air temperature conditions. Therefore, conducting thorough investigations into the seasonal behaviors of *S. tricuspis* across various countries is advised, considering the precise overwintering periods of larvae and pupae.

ACKNOWLEDGMENT

The authors acknowledge the support from Princess Nourah bint Abdulrahman University Researchers Supporting Project number (PNURSP2025R37), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia.

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