RENATA CORDEIRO DOS SANTOS

FIND WHERE THEY ARE: PREDICTING SUITABLE AREAS FOR THE INVASIVE SPECIES *Erthesina fullo* (HEMIPTERA: PENTATOMIDAE)

Dissertation submitted to the Entomology Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

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Marcelo Coutinho Picanço
Adviser

To my dad.

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To God, for creating and sustaining me throughout my existence!

To my parents, for teaching me how to walk and where to walk, and together with my brothers, making me sure that I will never be alone.

To my husband, for supporting and loving me. For being light and joy in my life.

To my friends, old and new, for being companions. For the esfihas eaten, for the brownies shared, for the coxinhas and churros savored, for being together.

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Surviving is not enough, live!!!

ABSTRACT

SANTOS, Renata Cordeiro dos, M.Sc., Universidade Federal de Viçosa, February, 2023. **Find where they are: predicting suitable areas for the invasive species *Erthesina fullo* (Hemiptera: Pentatomidae)**. Adviser: Marcelo Coutinho Picanco. Co-advisers: Ricardo Siqueira da Silva and Abraão Almeida Santos.

Erthesina fullo (Thunberg) (Hemiptera: Pentatomidae) is an invasive pest from Asia that was recently detected in Europe (2017) and South America (2021). This pest has a high risk of establishment in introduced areas due to polyphagia and adaptation to various temperatures. Yet, there are no data about potentially suitable areas for species occurrence outside its native range despite the recent invasion events. In this study, we presented a model for the potential distribution of *E. fullo* based on the CLIMEX algorithm. We created the model using global species occurrence (1424 points), three climate scenarios (current, 2030, and 2080), and biological information available. We then estimated the ecoclimate index and weekly growth index to determine the suitability of regions in a general scenario over time. Under the current climate scenario, our model demonstrates that suitable areas for *E. fullo* comprised America, Africa, Europe, and Oceania. These areas are inside tropical and subtropical climates. However, the suitability was reduced in those climates (-28%) under future climate scenarios, increasing in temperate regions. In addition, the weekly growth index of *E. fullo* was positively correlated with the photoperiod. Our study can guide future efforts to avoid potential invasion and establishment of *E. fullo* outside its current range.

Keywords: Invasion. Distribution modeling. Yellow-spotted stink bug. Biosecurity. CLIMEX. Climate change.

RESUMO

SANTOS, Renata Cordeiro dos, M.Sc., Universidade Federal de Viçosa, fevereiro de 2023. **Descubra onde eles estão: prevendo áreas adequadas para a espécie invasora *Erthesina fullo* (Hemiptera: Pentatomidae)**. Orientador: Marcelo Coutinho Picanço. Coorientadores: Ricardo Siqueira da Silva e Abraão Almeida Santos.

Erthesina fullo (Thunberg) (Hemiptera: Pentatomidae) é uma praga invasora da Ásia que foi recentemente detectada na Europa (2017) e América do Sul (2021). Esta praga apresenta alto risco de estabelecimento em áreas introduzidas devido à polifagia e adaptação a diversas temperaturas. No entanto, não há dados sobre áreas potencialmente adequadas para a ocorrência dessa espécies fora de sua área nativa, apesar dos recentes eventos de invasão. Neste estudo, apresentamos um modelo para a distribuição potencial de *E. fullo* baseado no algoritmo CLIMEX. Criamos o modelo usando a ocorrência global da espécies (1424 pontos), três cenários climáticos (atual, 2030 e 2080) e informações biológicas disponíveis. Em seguida, estimamos o índice de ecoclimático e o índice de crescimento semanal para determinar a adequação das regiões em um cenário geral ao longo do tempo. No cenário climático atual, nosso modelo demonstra que as áreas adequadas para *E. fullo* compreendem América, África, Europa e Oceania. Essas áreas estão dentro de climas tropicais e subtropicais. No entanto, a adequação foi reduzida nesses climas (-28%) em cenários climáticos futuros, aumentando nas regiões temperadas. Além disso, o índice de crescimento semanal de *E. fullo* correlacionou-se positivamente com o fotoperíodo. Nosso estudo pode orientar esforços futuros para evitar invasão potencial e estabelecimento de *E. fullo* fora de sua distribuição atual.

Palavras-chave: Invasão. Modelagem de distribuição. Percevejo fedorento de manchas amarelas. Biosseguridade. CLIMEX. Mudança climática.

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1 INTRODUCTION

International trade is one of the main routes of pest introduction in new areas. Future climate change scenarios can have synergistic effects enabling the establishment of introduced species (Clark, 2013; Bertelsmeier, 2021). International trade and climate change have been associated with successful species invasions in agricultural areas (Santana et al., 2019). However, the direct impact of climate on the suitability of areas varies among species (IPCC, 2014). Therefore, investigating potential areas for invasive species is helpful for biosecurity agencies under current and future climate scenarios.

Invasive species are a challenge to crop production due to the negative impact on crop yield, absence of control methods and native natural enemies to regulate population size, and legal regulations (Carruthers, 2003; Paini et al., 2016; Eschen et al., 2021). Native to Asia, *Erthesina fullo* (Thunberg) (Hemiptera: Pentatomidae), commonly known as the yellow-spotted stink bug, was recently found in Europe (2017) and Brazil (2021), threatening crop security (Lupoli et al. 2020; Brugnera et al. 2021). *Erthesina fullo* is a polyphagous species attacking 57 species from 29 botanical families (Mi et al., 2020). Losses are estimated at 30% in kiwifruit. Furthermore, the damage rate of this pest has reached 60% in pear and 20% in apple and macadamia in the area of origin (Lu et al., 1992; Zhang et al., 1993; Zhou et al., 2000; Wang & Kang, 2000; Tan et al., 2017; Zhang et al., 2019).

Until 2016, *E. fullo* distribution was restricted to the Asian continent. However, in 2017 this species was detected in Albania and recently (2021) in Sao Paulo state, Brazil (Lupoli et al., 2020; Brugnera et al., 2021). In 2014, individuals were intercepted in New Zealand but not detected again (Mitchell, 2014). These recent reports underscore the importance of *E. fullo* as a potential risk in new areas coupled with its capacity of dispersal through international trade and biological aspects such as development in a wide range of temperatures (5-36 ºC), high reproductive output (126-173 eggs per female), and hibernation that benefits the insect to overcome low-temperature winters (Lu et al., 1992; Zhou et al., 2000; Mi et al., 2020; Manaaki Whenua, 2022).

Predicting suitable sites for invasive species under current and future climate conditions provides essential information for biosecurity agencies to undertake actions to avoid introduction or, for those already introduced, underscore priority areas for monitoring (Santos et al., 2019; Businari, 2021; Manaaki Whenua, 2022). This can help agencies delimit areas for surveys and possible species eradication (Silva et al., 2017; Santana et al., 2019). Species distribution models (SDM) have been employed to estimate suitable areas for species occurrence. The models predict appropriate locations in a spatiotemporal context under current and future climate scenarios, indicating likely species responses to a variation in climate (Kumar et al., 2014; Santana et al., 2019).

CLIMEX software modeling is an example of SDM that uses a mechanistic approach that combines biological parameters of species development, and climate features to project suitable areas for potential species occurrence (Kriticos et al., 2015; Sutherst et al., 2007). This approach has been successfully applied to predict suitable areas for species, including *Halyomorpha halys* (*Stål*) (Hemiptera: Pentatomidae) which has a similar origin as *E. fullo (*Kriticos et al., 2017). In the 1990s, *H. halys* was accidentally introduced in North America and found in Europe in 2007. As a result, the species became established in different European countries, and its distribution has been associated with climate change (Callot & Brua, 2013; Stoeckli, Felber & Haye, 2020).

Due to recent invasions of *E. fullo*, understanding the potential species distribution under current and future climate scenarios will provide information that can help to reduce the likelihood of new invasions and establishment. The objective of this study was to determine potentially suitable areas for *E. fullo* with CLIMEX software.

2 MATERIAL AND METHODS

2.1 Climex

The software CLIMEX (version 4.0; Hearne Software) allows us to predict the spatiotemporal distribution of species under current and future climate scenarios (Kriticos et al. 2015). Based on biological parameters and present species occurrence data, this software generates an ecoclimate index (EI).

The EI combines a growth index based on temperature, humidity, and stress factors such as hot, cold, dry, and wet conditions and their interactions (Kriticos et al. 2015). The index represents an annual mean of suitable conditions for species occurrence represented by values from 0 to 100. EI = 0 means unsuitable conditions for species establishment, while those ≥ 30 suggest suitable species development and growth (Kriticos et al., 2015). Because the EI only reflects a general overview of suitability (i.e., annual mean), we also used the weekly growth index (GIw) to verify suitable conditions over months. The index varies from 0 to 1, where values close to 1 indicate better conditions for species growth (Kriticos et al., 2015).

2.2 Current occurrence data of *E. fullo*

The current occurrence records were obtained from the database of the Global Biodiversity Information Facility (GBIF), the Center for Agriculture and Biosciences International (CABI), and the European and Mediterranean Plant Protection Organization (EPPO). We also used Web of Science, Science Direct, and Google Scholar to confirm the initially obtained occurrence (Table S1, supplementary material). Our initial data consisted of 1479 points of occurrence. Then, we filtered the data to remove points without coordinates information, duplicate records, or suspected outliers (i.e., coordinates out of the species' range). As a result, our final dataset consisted of 1424 occurrence points (Fig. 1).

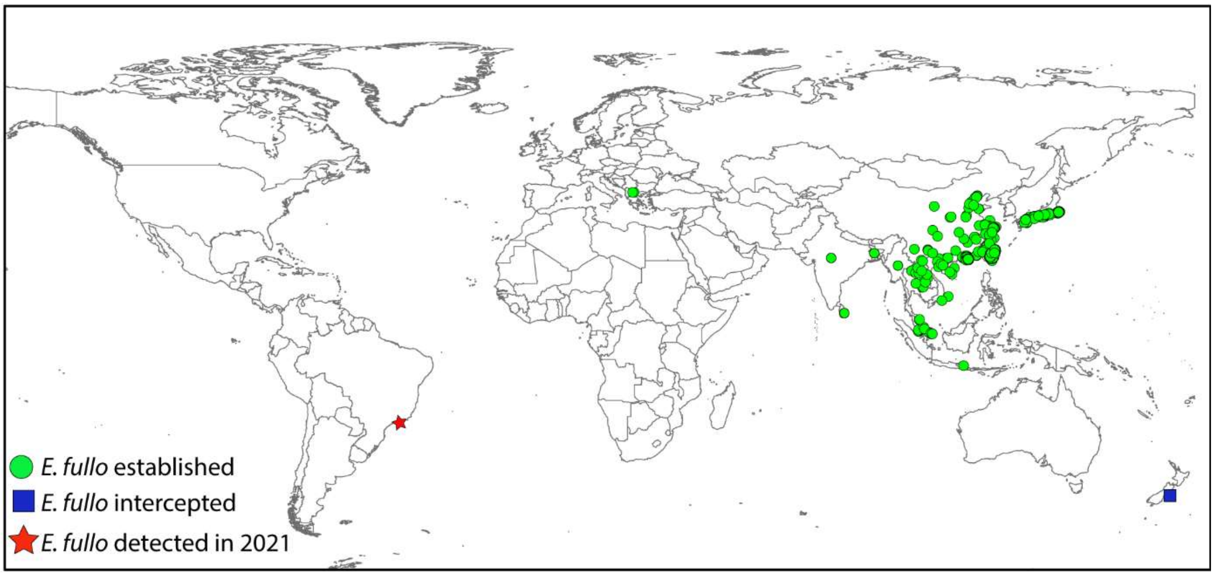

FIGURE 1- Occurrence data of *Erthesina fullo* under field conditions. The green circles indicate areas where species are established. The blue square indicates the *E. fullo* interception (New Zealand), and the red star is the last detection of *E. fullo* (São Paulo, Brazil).

Erthesina fullo is reported in 14 countries in Asia, Europe, Oceania, and recently South America (Fig. 1). In addition to its region of origin (Asia), the species is present in Europe (Albania) following its introduction in 2017 (Lupoli et al., 2020), and in South America (Brazil) in 2021. In New Zealand, one female was intercepted in 2014 (Teulon & Xu, 2018).

2.3 Model setup

We used the 1424 occurrence data points and biological parameters for *E. fullo* development to define model parameters. These data were combined with climate data to represent suitable areas based on the EI.

We used the CliMond 10' climate dataset, consisting of historical data for over 30 years (1961-1990), including monthly average maximum and minimum temperature, the sum of precipitation, and relative humidity at 09:00 and 15:00 h (Kriticos et al., 2012). To estimate the potential effect of climate change on species distribution, we used the climate change scenario A2 SRES and the global climate model CSIRO-Mk3.0 (Center for Climate Research, Australia) for the years 2030 and 2080. We chose these years because they indicate different increases in the global temperature (+0.98 °C in 2030, +2.88 °C in 2080), representing short and long time scenarios (Kriticos et al., 2012). The CSIRO-Mk3.0 model in its current form is as complete as any global coupled model available; the four major components of the climate system (atmosphere, land surface, oceans, and sea ice) are well represented. The A2 SRES scenario has relevant demographic, financial, and technological factors related to greenhouse gas (GHG) emissions. The A2 scenario assumptions include population and regional economic development data from independent, self-sufficient nations. The A2 scenario assumes relatively moderate increases in global GHG emissions that are also more realistic compared to other scenarios such as A1F1, A1B, B2, A1T, and B1 (Bernstein et al. 2007).

We fitted the model based on biological data of *E. fullo* and used the occurrence records to calibrate model parameters. The final model parameters are shown in Table

2.3.1 Temperature index

In Climex, four temperature parameters that define the population growth range are required: DV0 = the lower temperature threshold; DV1= the lower optimum temperature; DV2= the upper optimum temperature; DV3=the upper-temperature threshold (Kriticos et al., 2015).

The development of *E. fullo* occurs from 15 to 30 °C, with eggs hatching at a rate > 97.5% (Zhou et al., 2000). Thus, we used values of 5 °C (DV0), 15 °C (DV1), 30 °C (DV2), and 36 °C (DV3) (Table 1). DV0 and DV3 were based on two areas where *E. fullo* occurs in China (Henan and Xi'an) (Song & Wang, 1993; Feng, 2007), and these values presented a better model calibration (see final model parameters in Table 1).

TABLE 1 Parameters fitted in the model of *Erthesina fullo* using the Climex algorithm.

Index	Unit	Parameter	Values
Temperature	ºC	DV0= Limiting low temperature	5
	ºC	DV1= Lower optimal temperature	15
	ºC	DV2= Upper optimal temperature	30
	ºC	DV3= Limiting high temperature	36
Moisture	-	SMO= Limiting low moisture	0.1
	-	SM1= Lower optimal moisture	0.4
	-	SM2= Upper optimal moisture	1.5
	-	SM3= Limiting high moisture	2.5
Cold stress	ºC	TTCS=Cold stress temperature threshold	-20
		THCS=Cold stress temperature rate	-0.01
	ºC	TTHS=Heat stress temperature threshold	36
		THHS= Heat stress temperature rate	0.001
Diapause	Hours	DPD0= Diapause Induction Daylength	10.5
	ºC	DPT1= Diapause termination temperature	13
		DPSW= Diapause summer (1) or winter (0)	0

2.3.2 Moisture index

The moisture index values were based on the region of *E. fullo* abundance (Southeast Asia). Thus, values of moisture were set up to 0.10 (lower soil moisture threshold – SM0), 0.40 (lower optimum soil moisture – SM1), 1.5 (upper optimum soil moisture – SM2), and 2.5 (upper soil moisture threshold – SM3) (Table 1). These values provided better results for our model and matched the occurrence records.

2.3.3 Cold and heat stress

In Climex, cold and heat stress is defined as a set that limits the species' ability to survive during adverse seasonal conditions. Thus, we set a cold stress temperature threshold (TTCS) and a heat stress temperature threshold (TTHS) based on biological data and areas where the species mainly occurs.

Erthesina fullo has a diapause period induced by negative temperatures that favor the insect's survival during rigorous winters (Sibayan, 2018). We obtained those negative temperature values from Henan and Xi'an (China), where *E. fullo* occurs, and the lowest temperature registered was –22 °C (Tu tiempo, 2022). On the other hand, the related species *H. halys*, with a similar biology as *E. fullo*, has a lower thermal limit at -18ºC (Stoeckli et al., 2020). Thus, based on model calibration, we set the TTCS value at -20 ºC and TTHS at 36 °C (Table 1).

2.3.4 Reproductive diapause

In addition to hibernation during cold conditions, variations in photoperiod can induce a diapause in reproduction. of *E. fullo*. In Climex, this biological aspect is indicated by the average weekly day length that induces diapause (DPD0) and the average weekly minimum temperature for winter diapause that terminates diapause (DPT1). Thus, we set a diapause in the model at 10.5 hours/days as DPD0 and a temperature above 13°C as DPT1 (Zhang, 2018).

2.4 Model calibration and validation

We calibrated the model using the region of origin as an initial reference, literature data, and weather data from the occurrence region. We then adjusted values accordingly to match occurrence data (mechanical approach).

We validated the models using the EI and GIw. For EI, we noted how many occurrence points correspond with suitable areas for species growth (EI ≥30). In the case of GIw, we extracted the weekly values and compared those with *E. fullo* occurrence data in Shaanxi (China) in 2006 (Feng, 2007). Furthermore, as the reproductive diapause seems to be associated with photoperiod (Mi et al., 2020), we performed a Pearson correlation analysis (α = 0.05) between the GIw values and the photoperiod obtained from Shaanxi (China) in 2006 (Feng, 2007).

3 RESULTS

3.1 Potential distribution

The final model presented a great adjustment with all occurrence data inside areas with EI ≥ 30 (Fig. 2). In addition to the Asian continent, our model indicated that tropical and subtropical regions of Africa, America, Europe, and Oceania were suitable for *E. fullo* (Fig. 2). These places included the countries where the pest has been detected and intercepted, Brazil and New Zealand.

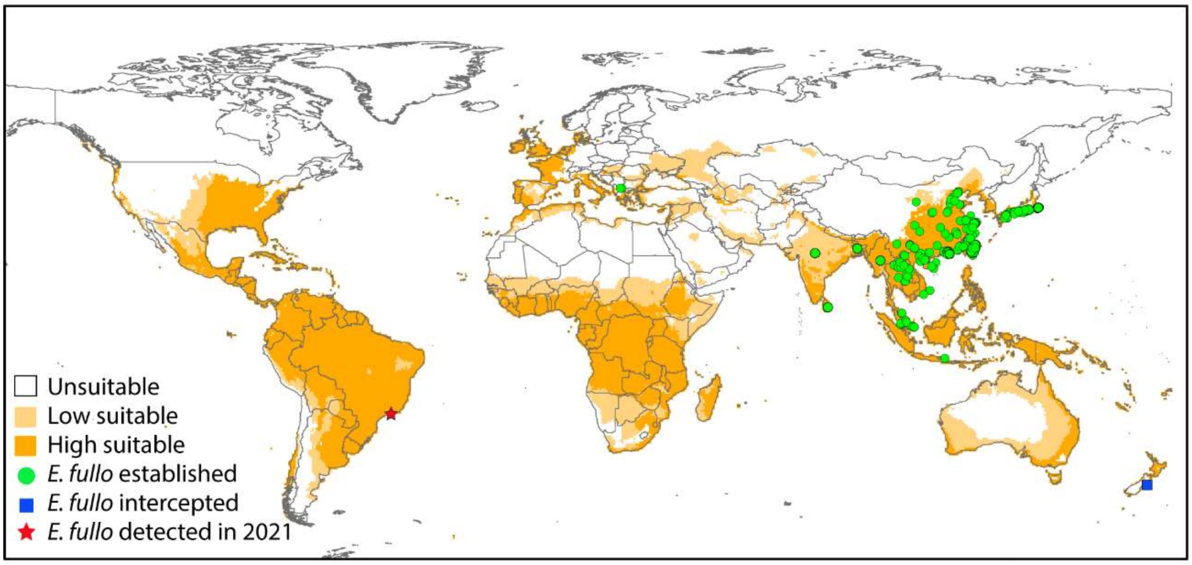

FIGURE 2 - Potential distribution of *Erthesina fullo* according to the Ecoclimate Index using CLIMEX. Unsuitable, low suitable, and high suitable are indicated by the EI equal to zero, 0<EI<30, and EI>30 up to 100.

3.2 Model validation based on GIw

We found a positive correlation between the GIw and photoperiod, indicating that increases in photoperiod appear to increase suitable conditions for species occurrence ($r = 0.61$, $t = 2.50$, $df = 12$, $P = 0.03$; Fig. 3). Remarkably, the high GIw values coincided with the reproductive season of *E. fullo*, and when it is reduced ties with the period of reproductive diapause (Fig. 3).

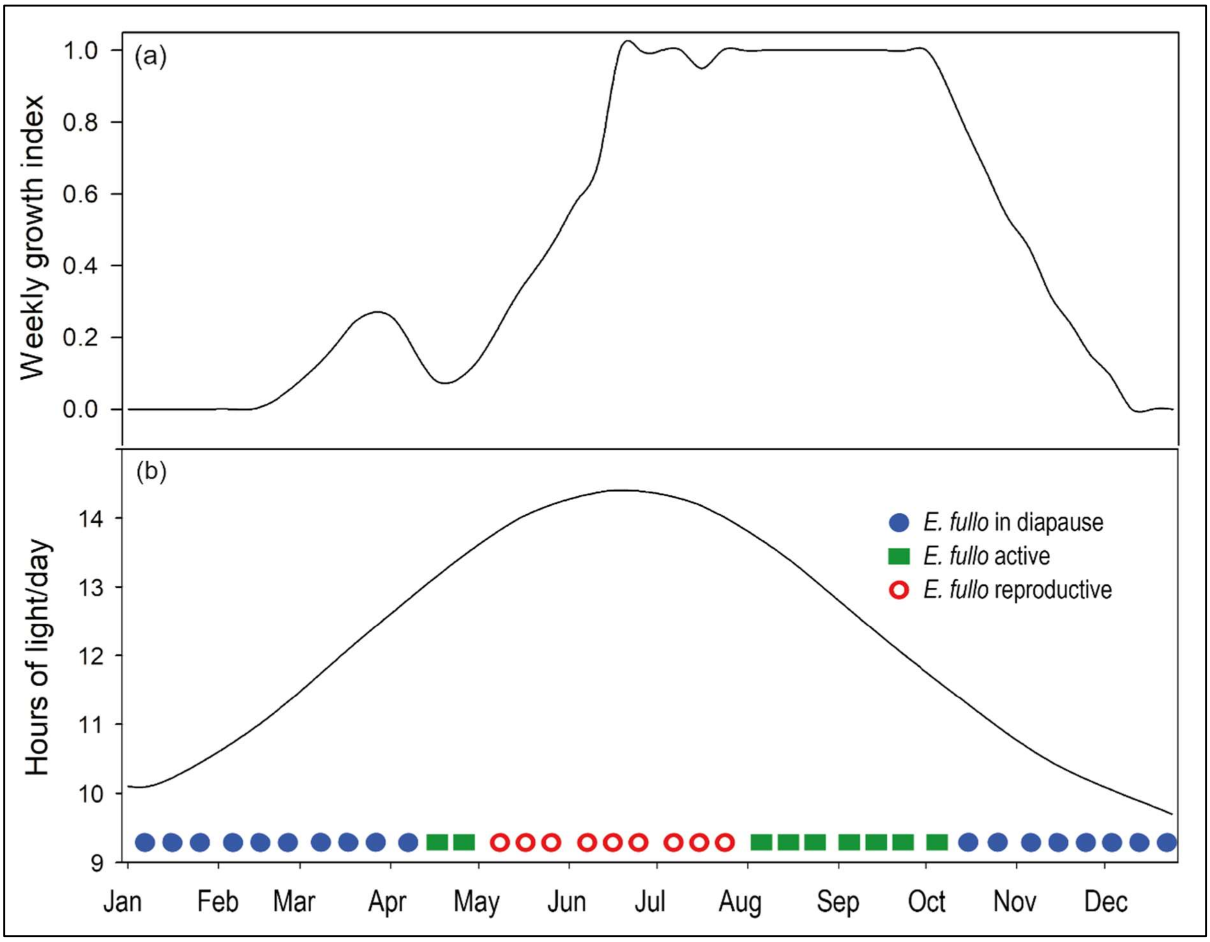

FIGURE 3 - The weekly growth index of (a) *Erthesina fullo* and (b) hours of light per day according to the month of the 2006 year in Xi'an (Shaanxi – China).

3.3 Future scenarios

In both future projections, 2030 and 2080, we noted that suitable areas for *E. fullo* reduced by 7.66% e 28.65%, respectively (Fig. 4). These decreases were primarily reported in America, Africa, and Oceania, indicating thermal stress as a possible harm factor for species. Nevertheless, in Europe, suitable areas increase for *E. fullo,* suggesting that high latitude areas will become suitable for the pest (Fig. 4).

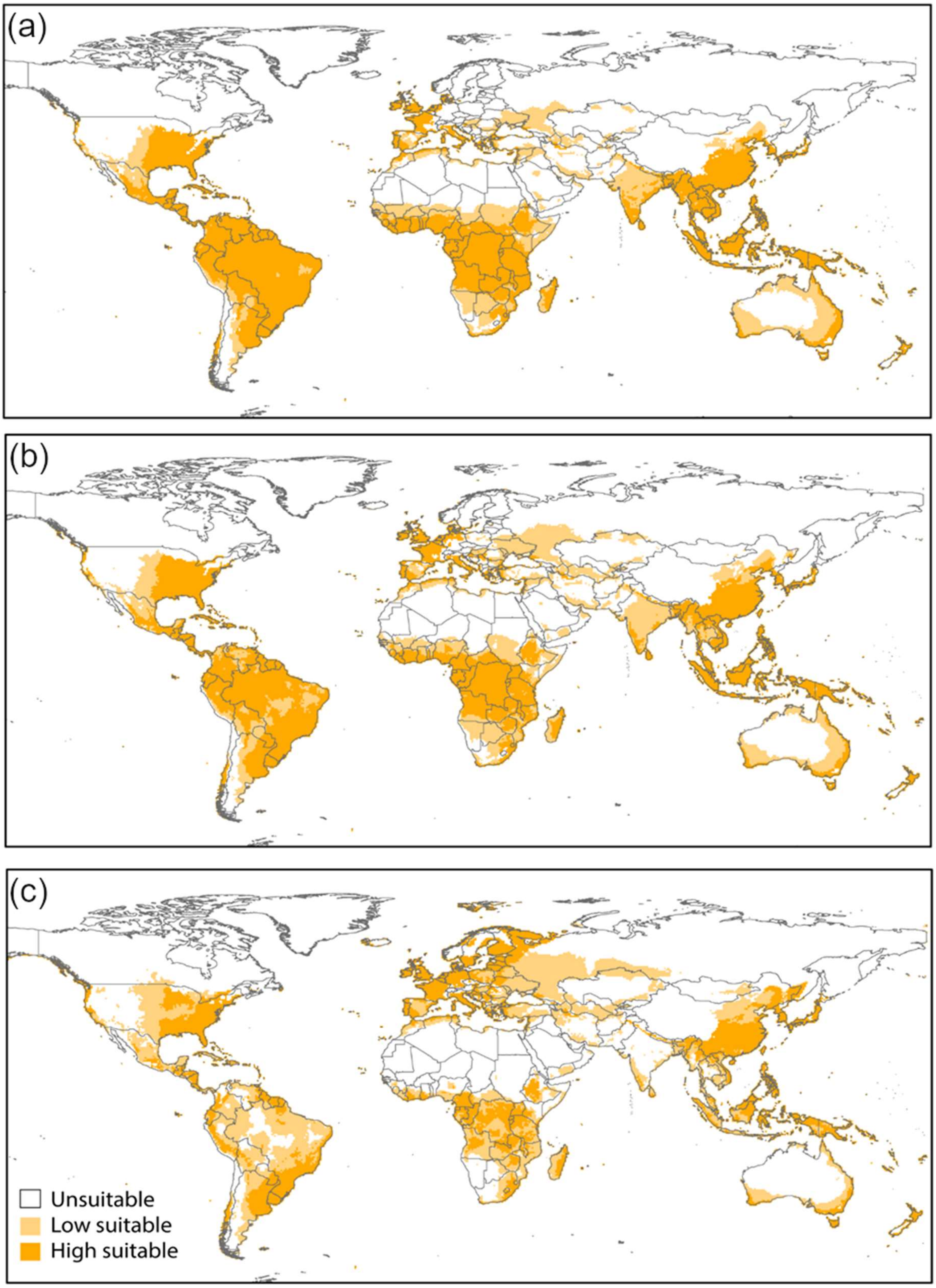

FIGURE 4 - Current (a) and future potential distribution of *Erthesina fullo* under scenarios SCIRO A2 to (b) 2030 and (c) 2080. Unsuitable, low suitable are high suitable indicate the EI equal to zero, 0<EI<30, and EI>30 up to 100.

4 DISCUSSION

Due to the recent invasion of *E. fullo*, models that predict suitable areas for this pest are needed to help biosecurity agencies create priority areas for inspection to avoid likely invasion and establishment. We provide a reliable model that indicates suitable areas for *E. fullo* under current and future scenarios. Subtropical and tropical regions are highly suitable for species occurrence in the current scenario, and photoperiod seems positively associated with species' reproductive season. Yet, suitable areas tended to decrease in subtropical and tropical areas under future scenarios while increasing in temperate regions.

Erthesina fullo is a potentially invasive species with a high risk for crop security due to its polyphagous habit, development in various temperatures, and hibernation as a survival strategy in cold conditions (Mi et al., 2020). Furthermore, 57 species are related to being the host of *E. fullo,* which favors species establishment in new areas. For instance, in Albany, this species was founded in Tilia cordata Miller (Malvaceae) and Ziziphus jujuba Miller (Rhamnaceae), while in Brazil, in Inga sp. (Fabaceae) (Brugnera et al, 2021; Lupoli et al., 2021). Intriguingly, these areas have contrasting weather conditions. For example, in São Paulo (Brazil), mean temperatures vary from 4 to 30 °C, while in Albany is from 13 to 28 °C (Zhou et al., 2000; Mi et al., 2020; Brugnera et al., 2021; Lupoli et al., 2021). Accordingly, *E. fullo* development may vary as univoltine, bivoltine, or multivoltine (Wang & Kang, 2000, Feng, 2007). This underscore that the species may have enough conditions to establish itself in new areas following its introduction. Furthermore, hibernation facilitates species continuity mediating survival under negative temperatures (Zhou et al., 2000). Thus, in addition to tropical areas, subtropical and temperate can also be suitable for species occurrence, as indicated in our model.

In Brazil, individuals of *E. fullo* are thought to be in the reproductive stage following its invasion (Brugnera et al., 2021). Due to high crop diversity, the country is at risk of establishing because the principal hosts of *E. fullo* are cultivated in large areas, such as orange, beetroot, guava, sugar cane, bamboo, apple, peach, pear, plum, grape, and tobacco (Mi et al., 2020). A plausible hypothesis is that *E. fullo* was introduced to the country through international trade since species were detected near the major Brazilian seaport at Santos municipality (São Paulo state). Likewise, individuals in Albania and New Zealand were founded around international trade seaport areas (Teulon & Xu, 2018). This route seems to be common for species invasion. The model presented here provides valuable information for monitoring and contingency of *E. fullo* in those areas, which can be priority areas for species eradication and continuous monitoring.

A related species of *E. fullo, H. halys*, underscores the importance of preventing species invasion and establishment in new areas. In addition to its origin in China, *H. halys* is also present in Europe and North America (Kriticos et al., 2017). After its introduction in the United States in 1990, in 2010, the economic losses caused by *H. halys* were estimated at US$37 million in fruit, horticulture, and row crops (Leskey & Nielsen, 2018). Therefore, it can be expected that *E. fullo* may cause similar losses as those reported to *H. halys* (Mi et al., 2020).

Using the GIw, we found a positive association with photoperiod, which is related to a variation in temperature, the main factor in insect biology, such as survival and reproduction (Dukes et al., 2009; Skendžić et al., 2021). Reduction in temperature coupled with photoperiod signals hibernation and reproductive diapause for *E. fullo* (Tougeron et al., 2020.). Our estimated GIw agrees with this event. When the photoperiod is lower than 10.5 hours/daily, the GIw was close to or equal to a zero, indicating unsuitability for the development of *Erthesina fullo*. In contrast, longer photoperiods correspond to the reproductive season of this pest. When the environment is unfavorable, *E. fullo* shelters underwood, straw, and houses until the hostile climate ends (Mi et al., 2020).

Future scenarios suggest a reduction in suitable areas for *E. fullo* in tropical regions while an increase in the temperate areas. *Erthesina fullo* is limited to low and high temperatures despite its high-temperature range. For instance, at 13 °C, the species is inactive (Zhang, 2018), while a temperature > 30° C reduces eggs hatch (Zhou et al, 2000). Thus, heat stress might be a limiting factor for *E. fullo* in tropical areas, while cold stress may be reduced in temperate regions, increasing suitable areas for species occurrence (Santana et al., 2019).

Our model did not incorporate other factors that regulate *E. fullo* population sizes, such as natural enemies, host phenology, and geographic barriers that can also act on reducing the probability of species establishment (Jarnevich et al., 2015; Soares et al., 2021). Also, the parameters used in the model were estimated from studies and areas of species occurrence. Though the thermal requirements for species development are still unknown, the model’s values might be used and confirmed in future studies.

5 CONCLUSION

Our study indicates potentially suitable areas for *E. fullo* under current and future scenarios. Tropical and subtropical regions, including those where the species has been detected, presented suitability for species occurrence. Conversely, temperate areas will be more suitable for species when cold conditions may be amended in future scenarios. Our results are worthwhile to biosecurity agencies since the species has been reported in recent invasions events and indicate suitable areas that demand intense survey, primarily those around seaports, which seem to be the main route of invasion of *E. fullo*.

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CONFLICT OF INTEREST

There was no conflict of interest regarding the preparation and submission of this manuscript.

AUTHORS CONTRIBUTIONS

RCS and MCP conceived the research. RCS, CVB, and RSS collected the data and generated the models. RCS and AAS wrote the manuscript. All authors read and approved the final manuscript.

REFERENCES

Bertelsmeier, C. (2021). Globalization and the anthropogenic spread of invasive social insects. *Current Opinion in Insect Science*, *46*, 16-23. DOI: 10.1016/j.cois.2021.01.006

Brugnera, R., Lima, Y., Grazia, J., & Schwertner, C. F. (2021). Occurrence of the Yellow-Spotted Stink Bug *Erthesina fullo* (Thunberg) (Hemiptera: Pentatomidae) in Brazil, a Polyphagous Species from Asia. *Neotropical Entomology*, 1-5. DOI: 10.1007/s13744-021-00924-9

Businari, M. (2021) *Espécie asiática de percevejo 'comilão' chega ao Brasil e acende alerta*. In: Uol notícias. Retrieved from https://noticias.uol.com.br/meio-ambiente/ultimas-noticias/redacao/2021/08/21/especie-asiatica-de-percevejo-comilao-chega-ao-brasil-e-acende-alerta.htm

Callot, H., & Brua, C. (2013). *Halyomorpha halys* (Stål, 1855), la Punaise diabolique, nouvelle espèce pour la faune de France (Heteroptera Pentatomidae). L'Entomologiste, 69(2), 69-71.

Carruthers, R. I. (2003). Invasive species research in the United States Department of Agriculture–Agricultural Research Service. *Pest Management Science*, *59*, 827-834. DOI: 10.1002/ps.616

Clark, N. (2013). Mobile life: biosecurity practices and insect globalization. *Science as Culture*, *22*, 16-37. DOI: 10.1080/09505431.2013.776366

Dukes, J. S., Pontius, J., Orwig, D., Garnas, J. R., Rodgers, V. L., Brazee, N., Cooke, B., Theoharides, K. A., Stange, E. E., Harrington, R., Ehrenfeld, J., Gurevitch, J., Lerdau, M., Stinson, K., Wick, R. & Ayres, M. (2009). Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? *Canadian Journal of Forest Research*, *39*, 231-248. DOI: 10.1139/X08-171

Eschen, R., Beale, T., Bonnin, J. M., Constantine, K. L., Duah, S., Finch, E. A., Makale, F., Nunda, W., Ogunmodede, A., Pratt, C. F., Thompson, E., Williams, F., Witt, A. & Taylor, B. (2021). Towards estimating the economic cost of invasive alien species to African crop and livestock production. *CABI Agriculture and Bioscience*, *2*, 1-18. DOI: 10.1186/s43170-021-00038-7

Feng, H. (2007). The occurrence and control of pests in kiwifruit orchards. *Northwest Horticulture*, 12, 22. In Chinese

IPCC(2014) Climate change 2014: synthesis report. In: Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 5th edn (eds Core Writing Team, R. K. Pachauri & L. A.Meyer) 151 pp. IPCC, Geneva

Jarnevich, C. S., Stohlgren, T. J., Kumar, S., Morisette, J. T., & Holcombe, T. R. (2015). Caveats for correlative species distribution modeling. *Ecological Informatics*, *29*, 6-15. DOI: 10.1016/j.ecoinf.2015.06.007

Kramer-Schadt, S., Niedballa, J., Pilgrim, J. D., Schröder, B., Lindenborn, J., Reinfelder, V., Stillfried, M., Heckmann, I., Scharf, A. K., Augeri, D. M., Cheyne, S. M., Hearn, A. J., Ross, J., Macdonald, D. W., Mathai, J., Eaton, J., Marshall, A. J., Semiadi, G., Rustam, R., Bernard, H., Alfred, R., Samejima, H., Duckworth, J. W., Breitenmoser-Wuersten, C., Belant, J. L., Hofer, H. & Wilting A. (2013). The importance of correcting for sampling bias in MaxEnt species distribution models. *Diversity and Distributions*, *19*, 1366-1379. DOI: 10.1111/ddi.12096

Kriticos, D. J., Webber, B. L., Leriche, A., Ota, N., Macadam, I., Bathols, J., & Scott, J. K. (2012). CliMond: global high-resolution historical and future scenario climate surfaces for bioclimatic modelling. *Methods in Ecology and Evolution*, *3*, 53-64. DOI: 10.1111/j.2041-210X.2011.00134.x

Kriticos, D. J., Kean, J. M., Phillips, C. B., Senay, S. D., Acosta, H., & Haye, T. (2017). The potential global distribution of the brown marmorated stink bug, *Halyomorpha halys*, a critical threat to plant biosecurity. *Journal of Pest Science*, *90*, 1033-1043. DOI: 10.1007/s10340-017-0869-5

Kriticos, D. J., Maywald, G. F., Yonow, T., Zurcher, E. J., Herrmann, N. I., & Sutherst, R. W. (2015). CLIMEX Version 4: Exploring the effects of climate on plants, animals and diseases. *Canberra: CSIRO*, 184.

Kogo, B. K., Kumar, L., Koech, R., & Kariyawasam, C. S. (2019). Modelling climate suitability for rainfed maize cultivation in Kenya using a Maximum Entropy (MaxENT) approach. *Agronomy*, *9*, 727. DOI: 10.3390/agronomy9110727

Kumar, S., Neven, L. G., & Yee, W. L. (2014). Evaluating correlative and mechanistic niche models for assessing the risk of pest establishment. *Ecosphere*, *5*, 1-23. DOI: 10.1890/ES14-00050.1

Leskey, T. C., & Nielsen, A. L. (2018). Impact of the invasive brown marmorated stink bug in North America and Europe: history, biology, ecology, and management. *Annual Review of Entomology*, *63*, 599-618. DOI: 10.1146/annurev-ento-020117-043226

Lu, X. X., Wu, X. C., & Wang, L. (1992). Bionomics and control techniques of *Erthesina fullo* (Thunberg) on jujube trees. *Plant Protection*, *18*, 30-32.

Lupoli, R., Van, T., & Heyden, P. D. (2020). *Erthesina Spinola*, 1837–a new alien genus for Europe found in Albania (Hemiptera: Pentatomidae). *Heteroptera Poloniae-Acta Faunistica*, *14*, 121-123. DOI: 10.5281/zenodo.3882222

Lupoli, R., Heyden, T., & Dioli, P. (2021). Confirmation of *Erthesina fullo* (Thunberg, 1783) (Hemiptera: Pentatomidae) in Albania and its host plants. *Heteroptera Polon-Acta Faunist*, *15*, 101-102. DOI: 10.5281/zenodo.4918310

Manaaki Whenua: Landcare Research. *Yellow spotted stink bug - Erthesina fullo* (Thunberg, 1783). In:. Retrieved from https://www.landcareresearch.co.nz/tools-and-resources/identification/pentatomidae/pentatomidae-factsheets/yellow-spotted-stink-bug/

Mi, Q., Zhang, J., Gould, E., Chen, J., Sun, Z., & Zhang, F. (2020). Biology, ecology, and management of *Erthesina fullo* (Hemiptera: Pentatomidae): a review. *Insects*, *11*, 346. DOI: 10.3390/insects11060346

Mitchell, C. (2014). *Yellow spotted stink bug found in NZ*. In: The Timaru Herald (2014). Retrieved from https://www.stuff.co.nz/business/farming/cropping/63163690/yellow-spotted-stink-bug-found-in-nz

Paini, D. R., Sheppard, A. W., Cook, D. C., De Barro, P. J., Worner, S. P., & Thomas, M. B. (2016). Global threat to agriculture from invasive species. *Proceedings of the National Academy of Sciences*, *113*, 7575-7579. DOI: 10.1073/pnas.1602205113

Ramos, R. S., Kumar, L., Shabani, F., da Silva, R. S., de Araújo, T. A., & Picanço, M. C. (2019). Climate model for seasonal variation in *Bemisia tabaci* using CLIMEX in tomato crops. *International Journal of Biometeorology*, *63*, 281-291. DOI: 10.1007/s00484-018-01661-2

Santana, P. A., Kumar, L., Da Silva, R. S., & Picanço, M. C. (2019). Global geographic distribution of *Tuta absoluta* as affected by climate change. *Journal of Pest Science*, *92*, 1373-1385. DOI: 10.1007/s10340-018-1057-y

Santos, A. A., Hogendoorn, K., Ramos, R. S., & Picanço, M. C. (2019). Distribution models for *Ascia monuste* and the host *Brassica oleracea* var. *capitata*. *Journal of Applied Entomology*, 143, 1043-1051. DOI: https://doi.org/10.1111/jen.12675

Skendžić, S., Zovko, M., Živković, I. P., Lešić, V., & Lemić, D. (2021). The impact of climate change on agricultural insect pests. *Insects*, *12*, 440. DOI: 10.3390/insects12050440

Sibayan, N. E (2018). Cold tolerance, diapause and winter survival of the brown marmorated stink bug (*Halyomorpha halys*. *All Master's Theses*. 890.

Silva, R. S., Kumar, L., Shabani, F., Silva, E. M., Galdino, T. V. S., & Picanço, M. C. (2017). Spatio-temporal dynamic climate model for *Neoleucinodes elegantalis* using CLIMEX. *International Journal of Biometeorology*, *61*, 785-795. DOI: 10.1007/s00484-016-1256-2

Soares, J. R. S., da Silva, R. S., Ramos, R. S., & Picanço, M. C. (2021). Distribution and invasion risk assessments of *Chrysodeixis includens* (Walker,[1858])(Lepidoptera: Noctuidae) using CLIMEX. *International Journal of Biometeorology*, *65*, 1137-1149. DOI: 10.1007/s00484-021-02094-0

Song, H. W., & Wang, C. M. (1993). Damage by *Halyomorpha halys* (Stal) and *Erthesina fullo* (Thunberg) to jujube trees and their control. *Entomological Knowledge*, *30*, 225-228.

Stoeckli, S., Felber, R., & Haye, T. (2020). Current distribution and voltinism of the brown marmorated stink bug, *Halyomorpha halys*, in Switzerland and its response to climate change using a high-resolution CLIMEX model. *International Journal of Biometeorology*, *64*, 2019-2032. Doi: 10.1007/s00484-020-01992-z

Sutherst, R. W., Maywald, G. F., & Kriticos, D. J. (2007). CLIMEX version 3: user's guide.

Tan, D.J.; Wang, W.L.; Chen, H.S.; Tan, Q.J.; Tang, X.H.; Zheng, S.F.; Huang, X.Y & Liang, F. (2017). The stink bugs that damage the *Macadamia ternifolia* F. Muell and control measures. *Agric. Res. Appl*. 1, 74–78. In Chinese

Teulon, D. A., & Xu, B. (2018). Biosecurity risks from stink bugs to New Zealand kiwifruit identified in Chinese language literature. *New Zealand Plant Protection*, *71*, 140-150. DOI: 10.30843/nzpp.2018.71.163

Tougeron, K., Brodeur, J., Le Lann, C., & van Baaren, J. (2020). How climate change affects the seasonal ecology of insect parasitoids. Ecological Entomology, 45(2), 167-181. Doi: 10.1111/een.12792

Tu tiempo.net. *Climate Henan*. In: Retrieved from https://www.tutiempo.net/clima/1993/ws-560650.html

Zhang, C. T., Li, D. L., Su, H. F., & Xu, G. L. (1993). A study on the biological characteristics of *Halyomorpha picus* and *Erthesina fullo*. *For. Res*, *6*(3), 271-275. In Chinese

Zhang, Y. (2018**)** The occurrence of stink bugs on kiwifruits. *Shanxi J. Agric. Sci*., 64, 27–28. In Chinese

Zhang, Z. F.; Dong, X. L.; Lian, S.; Wang, C. X & Li, B. H. (2019). The damage symptoms and control of stink bugs on apple. *Fruit Grow. Friends*, 1, 31–52. In Chinese

Zhou, Y. S., Yin, Z. H., Luo, G. L., Wang, S. L., Lu, J., Zhu, T. G., Fan, J. & Li, Z. X. (2000). Occurrence of *Erthesina fullo* Thunberg and its control. *J. Southwest Agric. Univ.*, 22, 234-236. In Chinese

Wang, H. Z. & Kang, Y. X. (2000). Control of yellow spotted stink bug on kiwifruit. *Northwest Hortic*., 2, 38–39. In Chinese

MATERIAL SUPPLEMENTARY

Continent	Country	Year	Reference
Asia	Bangladesh, China, Japan Indonesia, Índia, Laos, Malaysia, Myanmar, Sri Lanka, Thailand, Taiwan, Vietnam.	-	Ahmad, I. M. T. I. A. Z., Memon, N. A. S. R. E. E. N., & Kamaludin, S. (2004). A revision of hayline stink bug genus *Erthesina spinola* (Hemiptera: Pentatomidae: Pentatominae) and their clasdistics. Pakistan J. Zool, 36(4), 285-293. Doi: 0030-9923/2004/0004-0285 Kou, R., Tang, D. S., & Chow, Y. S. (1989). Alarm pheromone of pentatomid bug, *Erthesina fullo* Thunberg (Hemiptera: Pentatomidae). Journal of chemical ecology, 15(12), 2695-2702. Roychoudhury, N., & Joshi, K. C. (2011). New record of pentatomid bugs, *Erthesina fullo* Thunberg and *Halys dentatus* Fabricius (Heteroptera: Pentatomidae), feeding on Teak in Madhya Pradesh. Indian Journal of Forestry, 34(1), 117-120. Thu, P. Q. (2005). Forest invasive species and their impacts on afforestation in Vietnam. The unwelcome guests. Zhou, YS; Yin, ZH; Luo, GL; Wang, SL; Lu, J.; Zhu, TG; Fan, J.; Li, ZX. (2000). Occurrence of *Erthesina fullo* Thunberg and its control. J. Southwest Agric. Univ, 22, 234-236.
Oceania	Temuka/ New Zealand	2014	Mitchell, C. (2014). Yellow spotted stink bug found in NZ. In: The Timaru Herald (2014). Available em: https://www.stuff.co.nz/business/farming/cropping/63163690/yellow-spotted-stink-bug-found-in-nz

Europe	Albania	2017	Lupoli, R., Heyden, T., & Dioli, P. (2021). Confirmation of *Erthesina fullo* (Thunberg, 1783)(Hemiptera: Pentatomidae) in Albania and its host plants. *Heteroptera Polon-Acta Faunist*, 15, 101-102. Doi: 10.5281/zenodo.4918310
America	Brazil	2021	Brugnera, R., Lima, Y., Grazia, J., & Schwertner, C. F. (2021). Occurrence of the Yellow-Spotted Stink Bug *Erthesina fullo* (Thunberg)(Hemiptera: Pentatomidae) in Brazil, a Polyphagous Species from Asia. Neotropical Entomology, 1-5. Doi: 10.1007/s13744-021-00924-9