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Risk analysis for invasion of the forest pest *Paropsisterna bimaculata* present in Tasmania to areas of the world

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Abstract

Paropsisterna bimaculata is an important pest of eucalyptus species. The insect is consistently associated with severe defoliation in large crop plantations in Tasmania. Its attack causes a reduction in the volume of wood produced and in serious cases, the death of trees. Eucalyptus is the most important species in the global forestry sector and has economic importance in many countries. The extensive insect fauna associated with these species demonstrates the need for increasingly effective control and prevention methods, especially in relation to those regulated as quarantine pests. The objective of this study was to develop an ecoclimatic index model for *P. bimaculata* using the CLIMEX software, highlighting the potential distribution of *P. bimaculata* in the world and the areas at risk of introducing the insect into planted forest crops. The potential distribution of *P. bimaculata* showed high suitability in regions of Asia, Africa, Europe, Oceania and America, with greater probability in countries in Europe and South America. The results are mainly associated with regions with temperate climates. Furthermore, an area present in the South and Southeast regions of Brazil also showed an adequate distribution for the species. The model's results presented here can assist in developing strategies to prevent the introduction and establishment of *P. bimaculata* in eucalyptus crops worldwide.

Keywords: CLIMEX, ecological modeling, eucalyptus, invasive species, defoliating insects.

1 Introduction

The genus *Eucalyptus*, originally from Australia, has a great diversity of species that have successfully established themselves in practically all climatic zones of the country. Insects from the Chrysomelidae family are the main defoliators of eucalyptus plantations in Australia and feed on several species of the host plant (Grimbacher et al., 2011; Elek; Patel 2016). The country is home to around 43 native genera of chrysomelids, 15 of which occur on the island of Tasmania (Elek; Patel, 2016). Three main genera that include *Paropsis*, *Paropsisterna* and *Traquimela* specialized in several species of *Eucalyptus* in Tasmania (De Little, 2011).

Although several defoliant beetles have the potential to cause damage to eucalyptus crops, only two specimens require constant management programs in Tasmania in order to avoid losses in the productivity of commercial plantations, namely *Paropsisterna bimaculata* (Oliver, 1872) and *Paropsisterna agricultural* (Chapuis) (Coleoptera: Chrysomelidae) (Elliott et al., 1992; Elek; Patel, 2016).

In this context, previously described as *Chrysoftharta bimaculata*, the Tasmanian eucalypt leaf beetle, *Paropsisterna bimaculata*, was first identified in 1992 and is recognized as an important pest species in commercial eucalypt forests in the state (Edgar, 2011). Elek; Patel (2016), in a study carried out on *E. nitens plantations* in the surroundings of Tasmania, they described that the insect dominated six of the eight locations surveyed, demonstrating great dispersion throughout the area.

These beetles, in their adult stage, measure approximately 9-10 mm in length and 7 mm in width, and their colors vary from reddish-brown, after diapause, to light green during the summer (Leon, 1989; Candy, 1999; Edgar, 2011). The adult female lays her eggs in the foliage of the host eucalyptus and, after hatching, the larvae develop into four larval stages (Baker et al., 2002). Both larvae and adults feed on a variety of eucalyptus species, however, their main native hosts include *Eucalyptus regnans*, E. *delegatensis*, E. *oblique* and *E. nitens* (Elliotti et al., 1992; Baker et al., 2002).

Candy (2000), demonstrated that during the rotation of an *E. nitens plantation* in Australia, severely attacked by defoliant beetles, the volume of wood harvested was reduced by up to 50%, indicating that uncontrolled defoliation by these insects can significantly reduce tree growth rates and generate major economic losses in forest plantations.

Eucalyptus leads the list of species in the forestry sector, in terms of importance (Júnior; Colodette, 2013). China, the United States and Russia hold around 41% of the world's planted forest areas. However, countries such as Canada, Sweden, India and Brazil increased their percentage share in areas made up of planted forests (Moreira Jmmap; Oliveria, 2016). The crop has been planted outside its place of origin for more than a century and, simultaneously, many native herbivorous insects have also spread to plantations around the world. However, few natural enemies of these pests followed the same paths (Elek; Patel., 2016).

Pest surveillance and control are essential, especially in the context of quarantine pests, due to their high potential to cause economic, social and environmental damage (MAPA, 2020). *P. bimaculata* is on the list of quarantine pests in eucalyptus-producing countries, such as New Zealand (Murray & Lin, 2017), and in the United States (Kliejunas et al., 2003). The species was also recently included in the list of quarantine pests absent from Brazil (MAPA, 2020).

In view of the above, there was a need to know the current and potential future distribution of *P. bimaculata*, aiming to generate information for planning and establishing measures in prevention to prevent its dispersion around the world. The lack of information about the species' propagation potential reinforces this need.

Exotic species are introduced and settle in new locations in a variety of ways, as a result of intentional or accidental dispersal. Kriticos et al. (2015) describe that the dispersion of these species around the world is mainly linked to the increase in commercial relations between countries, where the spread becomes worrying, as trade and tourism are the main routes for the worldwide dispersion of the species.

According to Paini et al. (2018), for the establishment of an invasive species in a new location to be effective, the probability of introduction and survival of the species must be considered, in terms of the initial number of individuals and tolerance to the characteristics of the region, such as the climate.

You models in niche ecological (MNEs) are tools capable of predicting the distribution potential of species, considering their ecological needs and available environmental conditions (Sutherst et al., 2007; Amaral et al., 2013). There are several bioclimatic models for species distribution, such as the generalized linear model (GLM), MaxEnt, Boosted Regression Tree (BRT), Bioclim, Random Forest (RF) and Insect Life Cycle Modeling (ILCYM) (Dos Santos et al., 2022). Among them, the Climex Program stands out (Sutherst et al., 2007), in studies involving pest risk assessments (Kriticos et al., 2015). Climex models are capable of projecting potential areas of distribution of species based on climatic factors, and their adjustments are made based on occurrence data and data biological of the species of interest (Kriticos et al., 2015).

Climex software uses values for a set of parameters related to temperature, soil humidity and luminosity, for example, according to the requirements of the species studied (Kriticos et al., 2015). The annual growth index (GIA) refers to the growth potential of the species under conditions favorable to its establishment, while four other stress indices (Cold (CS), heat (HS), wet (WS) and dry (DS)), and in some cases, their combinations, demonstrate conditions in which the establishment of the species is limited (Kriticos et al., 2015). The interaction of these growth and stress indices generates the Ecoclimatic Index (IE), which determines areas with suitable or unsuitable climatic conditions for the species (Kriticos et al., 2015).

Therefore, our objective was to determine the ecoclimatic index for the current climate scenario and potential future distribution for *P. bimaculata*, highlighting areas at risk of introduction in the world.

2 Material and methods

2.1 CLIMate indEX

CLIMEX is a computational tool that makes it possible to study the effects of climatic conditions, by creating maps that establish the relative abundance, seasonal variation and potential distribution of a species (Kriticos et al., 2015; Byeon; Jung; Lee, 2018). The CLIMEX model is based on estimates that allow the appropriate climatic conditions for the study species to be deduced when its biological parameters are known (Byeon; Jung; Lee, 2018). In this study, the software was used to determine the climatic suitability for *P. bimaculata* worldwide.

To adjust the model in CLIMEX and establish biological parameters, such as growth indices (i.e. temperature limits, humidity conditions and minimum growth degree-days) and stress indices (i.e. stress due to cold, heat, humidity and dry) climatic conditions and known records of the species distribution were used (Edgar. (2011), Elek; Patel. (2016); Nahrung et al. (2004); Fanning; Baars. (2014); Pinkard et al. (2017)). The model was generated by combining growth and stress indices, based on the ecoclimatic index (IE), scaled in a range from 0 to 100, where zero represents places where there is no climate suitability and values above 30 identify areas of high climate suitability for the species. The IE is obtained by multiplying the annual growth index (TGI), stress index (IS) and the interaction stress index (SX).

$$EI = TGI \times SI \times SX \text{ (Kriticos et al., 2015).}$$

2.2 Occurrence of *Paropsisterna bimaculata*

The survey of occurrence records of *P. bimaculata* was carried out using global distribution databases: *Global Biodiversity Information facility* (GBIF), *European and Mediterranean Plant Protection Organization* (EPPO) Global Data base It is literature published (Clarke. (1998); Candy. (2000); Elek; Patel. (2016); Nahrung; Reid (2002); Nahrung et al. (2004); Fanning; Baars. (2014); Pinkard et al. (2017)), totaling 47 occurrence points across the state of Tasmania. There are records of four interceptions of *P. bimaculata* by the United Kingdom quarantine in 2004, but the pest is currently absent in the country (CSL, 2005). In Then, the points were mapped with the help of ArcMap 10.5 software, to verification from the current distribution of the species and reserved for model validation.

2.3 Climate Data

We used the CliMond 10' spatial resolution historical dataset for the period 1981-2010 (30 years centered on 1995), from the Worldclim and Climate Research Unit (CRU) datasets (CL $_{1.0}$ and CL $_{2.0}$) (Kriticos et al., 2012), to perform modeling of *P. bimaculata*. This data set corresponds to local climate data, with monthly average values of minimum temperature (Tmin), monthly maximum temperature (Tmax), total monthly precipitation (Ptotal) and relative air humidity at 09:00 hours (RH 0900) and relative humidity at 15:00 hours (RH 1500). These data are of high quality and provide good spatial resolution, which is why we used them to develop our model.

2.4 CLIMEX parameters

CLIMEX parameters were established with reference to known distribution data for the species, in order to define a general index of climatic suitability for *P. bimaculata* in a given location. Once this was done, biological parameters related to population growth and stress were adjusted. These values were based on published work on the characteristics and climatic requirements for the development of *P. bimaculata* ((Clarke. (1998); Candy. (2000); Elek; Patel. (2016); Nahrung; Reid (2002); Nahrung et al. (2004); Fanning; Baars. (2014); Pinkard et al. (2017)).

Growth parameters

To define the appropriate conditions for the population growth of *P. bimaculata*, eight parameters represented by temperature and humidity indices were adjusted. Temperature parameters are indicated by DV0: Lower temperature limit, DV1: Lower ideal temperature, DV2: Upper ideal temperature and DV3: Upper temperature limit. Humidity parameters are indicated by SM0: Lower humidity limit, SM1: Lower ideal humidity level, SM2: Upper ideal humidity level and SM3: Upper humidity limit.

Temperature indices

Tasmania is characterized by a temperate maritime climate with hot, mild summers and cold, rainy winters, with four distinct seasons (Grose et al., 2010). Under the Köppen-Geiger climate classification, the region has a predominantly oceanic climate *(Cfb)*, and in the central highlands a subpolar oceanic climate *(Cfc)*, while in the far north and on King Island, a cool-summer Mediterranean climate *(Csb)*.

The emergence and oviposition of adult *P. bimaculata* insects is dependent on the combination of photoperiod and local temperatures. However, adults generally emerge during the winter, when they feed and lay eggs until diapause begins during the months of March and April (Nahrung; Allen, 2004; Elek; Patel, 2016). Temperature index values were adjusted based on the distribution of *P. bimaculata*, considering the emergence of adult insects during winter (Elek; Patel, 2016) and published studies (Clarke, 1998; Candy, 2000), which sought to define the time of peak occurrence for different larval instars of *P. bimaculata*.

Given this context, the thermal survival requirements for *P. bimaculata* were defined as DV0 = 0 ºC and DV3 = 30 ºC (Clarke, 1998; Candy, 2000). Furthermore, a temperature range between 20 ºC and 24 ºC was classified as being very suitable for the population growth of *P. bimaculata*, thus, DV1 and DV2 were defined at 20 ºC and 24 ºC, respectively, demonstrating that the insect is capable to survive large variations in temperature.

Moisture

The humidity parameters were defined as SM0= 0.1, SM1= 0.7, SM2= 1.5 and SM3= 2.5, values representative of the distribution in regions with a temperate climate, where the species occurs exclusively.

The modeling of insect species, although they may not be living directly in the soil environment, is strongly influenced by the soil moisture relationships of their hosts. In this sense, it is appropriate that the SM0 and SMDS values are 0.1, considering that the permanent wilting point of plants is around 0.1 (Kriticos et al., 2015).

Cold stress

Although *P. bimaculata* is a species adapted to regions with temperate climates and resistant to low temperatures, cold stress can cause the death of a species when daily thermal accumulation is insufficient to maintain metabolism. In CLIMEX, cold stress parameters are represented by DTCS: Cold stress degree-day threshold; DHCS: Cold Stress Temperature Rate. Therefore, DTCS was set at 9 and DHCS at –0.0003. These values provided a good fit to the known distribution of *P. bimaculata*.

Heat stress

In CLIMEX, TTHS represents the thermal stress parameter and THHS the thermal stress accumulation rate. Defoliator mortality may increase under heat waves, but upper temperature limits have not been documented for most species.

Candy. (2000), when carrying out predictive models for the integrated management of *P. bimaculata* , adopted the value of 30 ºC as the maximum upper temperature for its survival, considering that higher temperatures can harm the health and cause the death of insects. Similar results were found for the species *Paropsis atomaria* Olivier (Coleoptera: Chrysomelidae), a leaf beetle, a subfamily to which *P. bimaculata also belongs*. Thus, TTHS was set at 30 ºC and THHS was set at 0.01 week $^{-1}$ for *P. bimaculata*.

Dry stress

The known distributions of *P. bimaculata* are recorded exclusively in Tasmania, which has a temperate climate. The dry stress threshold (SMDS) was set at a value of 0.1 and the dry stress accumulation (HDS) at a rate of -0.95 week $^{-1}$. These values explain the low suitability for *P. bimaculata* in tropical and humid countries.

Wet stress

High precipitation can cause insect mortality. Excess rainfall is presented as a variable with a strong relationship with the abundance of *P. bimaculata*. Edgar (2011) describes that high precipitation, with rainfall above 200 mm, is associated with a sharp drop in beetle populations. Thus, the wet stress parameter (SMWS) was set at 2.5 and the wet stress accumulation rate (HWS) was set at 0.002 week $^{-1}$. The fixed values showed a satisfactory fit with the distribution of *P. bimaculata.*

2.5 Model validation

To validate the model, the maps of known occurrence points of *P. bimaculata* and the model generated in CLIMEX were overlaid using ArcMap 10.5 software to check whether the results found were consistent between the current distribution of *P. bimaculata* in Tasmania, in the United Kingdom, where the species has been eradicated, and the ecoclimatic index drawn up on the maps generated by CLIMEX, in the current climate scenario. The percentage of the species occurrence points that fitted the model's prediction was calculated to assess its reliability.

The adjusted values for the species are shown in Table 1.

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Table 1- CLIMEX parameter values used to model the distribution of *Paropsisterna bimaculata*

Index	Parameter	Acronym	Value	Reference
temperature	Lower temperature limit (°C)	DV0	0	Elek; Patel. (2016); Clarke. (1998); Candy. (2000).
	Lower optimal temperature (°C)	DV1	20	Candy. (2000).
	Upper optimal temperature (°C)	DV2	24	Candy. (2000).
	Upper temperature limit (°C)	DV3	30	Fanning; Baars

				(2014) ; Pinkard et al. (2017); Candy. (2000).
Moisture	Limiting low soil moisture	SM0	0.1	
	Lower optimal soil moisture	SM1	0.7	
	Upper optimal soil moisture	SM2	1.5	
	Limiting high soil moisture	SM3	2.5	
Stresses	Cold stress degree day threshold	DTCS	9	
	Cold stress degree day rate	DHCS	-0.0003	
	Heat stress temperature threshold (°C)	TTHS	30	
	Heat stress accumulation rate (week−1)	THHS	0.01	
	Dry stress threshold	SMDS	0.1	
	Dry stress rate (week−1)	HDS	-0.95	
	Wet stress threshold	SMWS	2.5	
	Wet stress rate (week−1)	HWS	0.002	

3 Results

Paropsisterna bimaculata is currently concentrated entirely in Tasmania, an island belonging to Australia, in different regions (Figure 1AB). There are records in the scientific literature that demonstrate that the species has already been intercepted a few times in the United Kingdom (Figure 1AC). However, it was eradicated by the country's plant protection services.

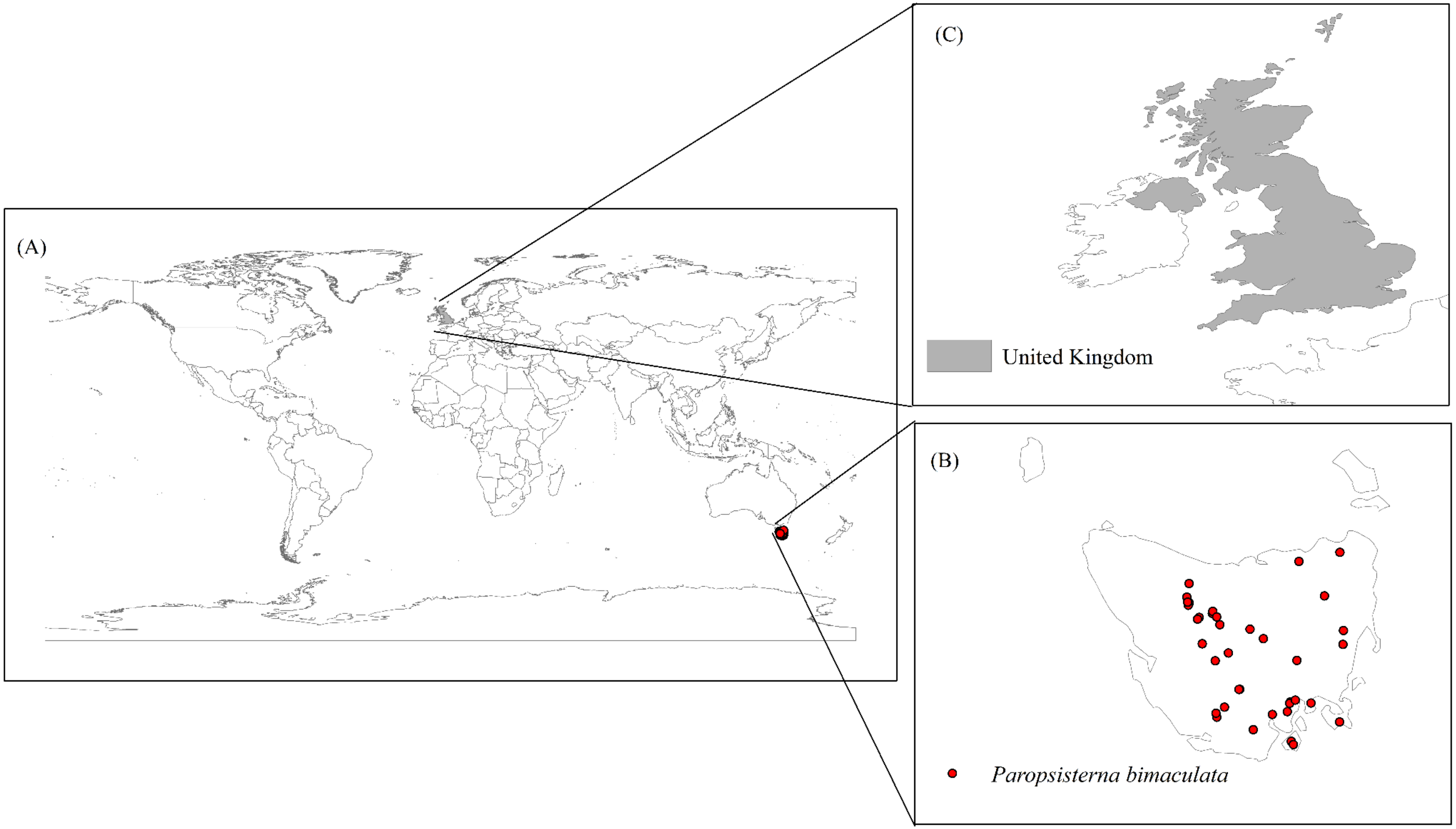

Fig. 1- (A) Current distribution of *Paropsisterna bimaculata* in the world and (B) in Tasmania; and (C) record of interception and eradication of *P. bimaculata* in the United Kingdom.

The potential distribution model of *P. bimaculata* corroborates the known distribution of the species. The overlay of the created maps demonstrated high suitability of the current distribution of *P. bimaculata* and the model based at the index ecoclimatic generated for the CLIMEX at the current scenario climate, as seen in (Figure 2). The sensitivity of the model showed 100% agreement with the known distribution of the species, indicating that the model is highly reliable.

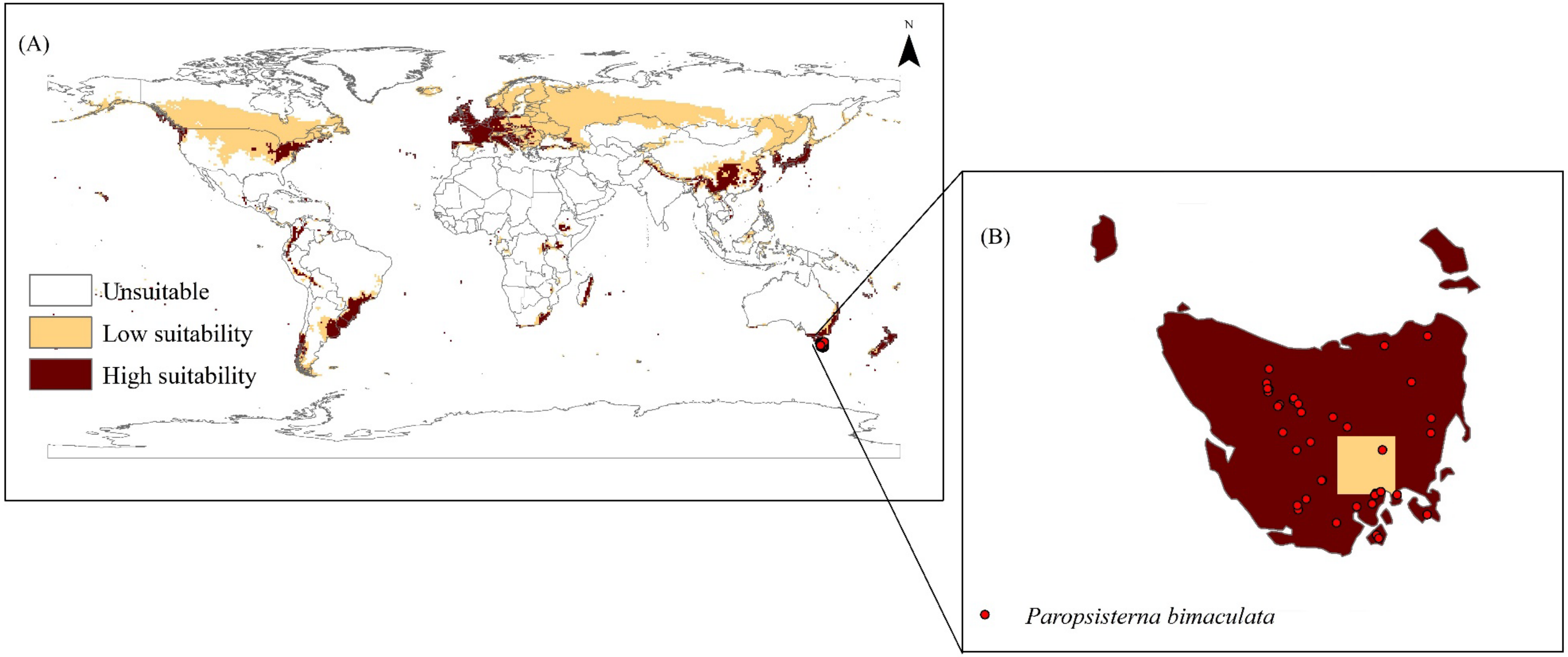

Fig. 1- Ecoclimatic Index (IE) model for the current climate scenario of the pest *Paropsisterna bimaculata* in the world (Figure 2A), and in Tasmania (Figure 2B), where its distribution of the species is known.

Paropsisterna. bimaculata was found on five continents, with greater evidence of suitable areas in Europe and America. As shown in Figure 3, the regions that are suitable for the establishment of the species include countries located on the European continent, such as United Kingdom, Ireland, France, Spain, Portugal, Netherlands, Belgium, Germany, Croatia, Italy, Austria, Poland and Denmark (Figure 3A). Countries on the Asian continent: China, India, Korea, Russia, Japan and Taiwan (Figure 3B). In Africa: South Africa, Madagascar, Ethiopia, Uganda and Kenya (Figure 3C). And in Oceania, South Australia, the state of Tasmania, and New Zealand (Figure 3D). Ideal conditions for the establishment of the pest species were also found in South American countries, including the southern and southeastern regions of Brazil, Chile, Argentina, Uruguay, Bolivia, Peru, Ecuador, Colombia and Venezuela (Figure 3E). And in North America: In the United States of America, Canada and Mexico (Figure 3F).

The altitude values of the 47 points of known occurrence of *P. bimaculata* were collected using the ArcGis 10.5 software. It was observed that only 6 occurrences of the species were detected at altitudes of up to 100 m, 14 points were detected at altitudes of 100 m to 500 m and 27 points were located at altitudes above 500 m. Edgar (2011) describes that high populations of *P. bimaculata* are associated with higher altitudes in Tasmania.

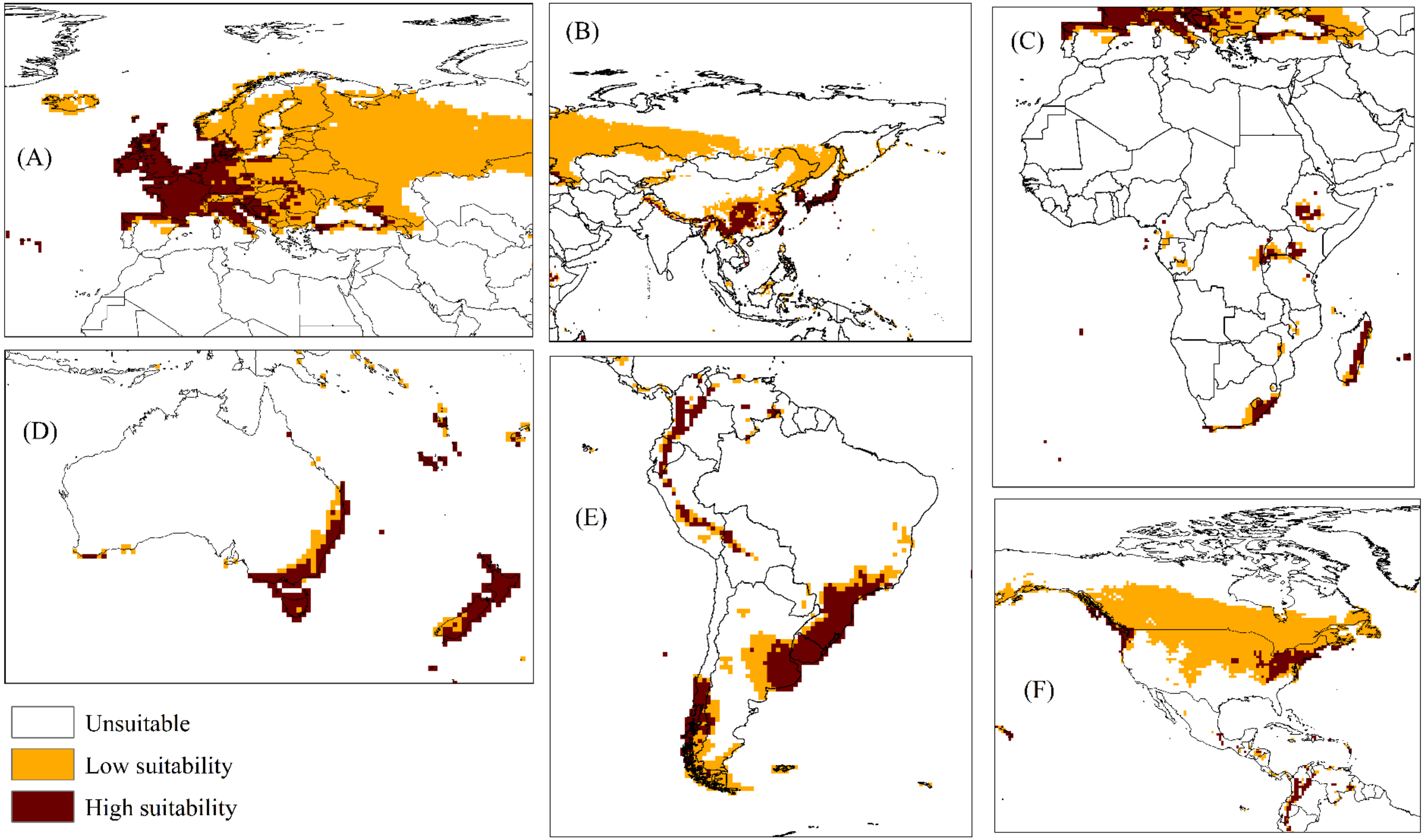

Fig. 2- Potential distribution of *Paropsisterna bimaculata* in validation regions based on the Ecoclimatic Index (IE) in Europe (A); Asia (B); Africa (C); Oceania (D) and South (E) and North America (F).

4 Discussion

The model generated by CLIMEX proved to be accurate and reliable in presenting climatic suitability for *P. bimaculata* in all locations where its occurrence is known in the state of Tasmania. This suggests that the biological parameters and environmental variables used are appropriate, and that the model can be an efficient tool in the management and monitoring of this pest. Forestry in Tasmania accounts for 39% of the state's forest areas. The northeast region has the largest area of eucalyptus forests, and is also where the highest incidence of *P. bimaculata is concentrated* (Edgar, 2011). However, the distribution data collected in the present study demonstrates a wide dispersion of the species throughout the state.

Although *P. bimaculata* is an endemic species to Tasmania, there are reports of its occurrence in the United Kingdom, through a non-host plant (Pteridofilas manferns), which demonstrates its ability to disperse also in non-host materials (Horgan, 2011; Elek; Wardlaw , 2013). The high suitability for the species in the United Kingdom ($30 \leq EI \leq 100$), even though its occurrence does not currently occur there, is an indication of good consistency and reliability of the model generated by CLIMEX.

In addition to the possibility of movement of the pest species from ferns, *P. bimaculata* can also be transported from ornamental eucalyptus, cut foliage and wood (CSL. 2005). The species is on the list of quarantine pests potentially associated with eucalyptus bark and New Zealand lumber (Anon . 2003ab). Kliejunas (2003), describes that the species was also included in the list of exotic pests capable of arriving in the USA along with eucalyptus logs and wood chips imported from Australia. Both countries present good conditions for the survival of *P. bimaculata* .

The introduction of an exotic species can occur through different routes, such as commercial, timber, merchandise, vegetable and international tourism routes. (Zhao et al., 2021) . Furthermore, around 70% of products imported and exported between countries are transported using wooden packaging, which can harbor pest species (Eyre et al., 2018). Our model presents areas of high suitability ($30 \leq EI \leq 100$) for the survival of *P. bimaculata* in the world's main eucalyptus producers, which include Brazil, China, India and Australia (Lee et al., 2023). These countries stand out for having extensive areas of eucalyptus plantations intended for different uses such as the production of cellulose, wood and essential oils (Lee et al., 2023).

China has the largest area of planted forests in the world (Zhao et al., 2021), followed by India which occupies second place (Trabado ; Wilstermann, 2008), highlighting the importance of measures to prevent the introduction of the species in these countries, although there is no record of *P. bimaculata occurring* in these locations.

On the Latin American continent, the high suitability for establishment of *P. bimaculata* maximizes the need for preventive measures to ensure sanitary quality and the commercial relationship between you countries members of Mercosur (Carneiro ; Galvão, 2017). Brazil is responsible for around 20% of all global crop production, estimated at 19.6 million hectares, according to data from GIT Foresty Consulting, and is recognized worldwide as a major producer of forest stands (Trabado & Wilstermann, 2019) .

Eucalyptus is the second most cultivated forest species in the southern region of Brazil, with production destined for cellulose, paper and energy (Auer ; Santos, 2011). Despite plantations in eucalyptus yet occur in form limited at region, due the occurrence of frosts and climatic conditions that reduce the number of species that adapt Under these conditions (Muller et al., 2017), studies have been frequent aimed at selecting species with tolerance to low temperatures, as an alternative to maximize the production in colder regions (Konzen et al., 2017). Currently, the South and Southeast regions represent a large part of Brazil's forestry production, representing around 70.6% of the value of national production, according to data from the Institute Brazilian Geography and Statistics (http://www.ibge.gov.br), demonstrating the importance of regions for Brazilian forestry.

Although the findings are useful for developing preventive strategies regarding the introduction and establishment of *P. bimaculata* in eucalyptus crops, limitations related to the model, such as dependence on climatic data, complexity of the real ecology and the adaptive capacity of the species, must be taken into account. in consideration. It is important to highlight the need for additional research, in search of more in-depth information on the characteristics of infestations and behavior of leaf beetles. Our results are starting points for future studies to prevent the introduction of *P. bimaculata* into suitable regions around the world.

5 Conclusion

The model showed high suitability in regions of Asia, Africa, Europe, Oceania, South America and North America, mainly in regions with a temperate climate. With greater representation in America and Europe. The ecological niche model results presented here provide a useful tool for developing strategies to prevent the introduction and establishment of *P. bimaculata.* in natural eucalyptus cultivation and planted forests. Pest Risk Analysis must be conducted to identify in advance the dangers and risks of invasion of exotic pests, especially quarantine pests, in countries and regions of high importance for global forestry.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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