UNIVERSIDADE FEDERAL DE VIÇOSA

Artificial intelligence tools for projecting failures in tomato leafminer control by insecticides

Jhersyka da Silva Paes
Doctor Scientiae

VIÇOSA - MINAS GERAIS
2025

JHERSYKA DA SILVA PAES

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Thesis submitted to the Plant Production Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

Adviser: Marcelo Coutinho Picanco

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Ficha catalográfica elaborada pela Biblioteca Central da Universidade Federal de Viçosa - Campus Viçosa

T

P126a
2025

Paes, Jhersyka da Silva, 1991-
Artificial intelligence tools in projecting failures in tomato leafminer control by insecticides / Jhersyka da Silva Paes. – Viçosa, MG, 2025.
1 tese eletrônica (65 f.): il. (algumas color.).

Texto em inglês.
Orientador: Marcelo Coutinho Picanço.
Tese (doutorado) - Universidade Federal de Viçosa, Departamento de Agronomia, 2025.
Inclui bibliografia.
DOI: https://doi.org/10.47328/ufvbbt.2025.544
Modo de acesso: World Wide Web.

1. Tomate - Doenças e pragas - Controle. 2. Plantas - Efeito dos inseticidas. 3. *Phytorimaeia absoluta*. 4. Inteligência artificial. I. Picanço, Marcelo Coutinho, 1958-. II. Universidade Federal de Viçosa. Departamento de Agronomia. Programa de Pós-Graduação em Fitotecnia. III. Título.

CDD 22. ed. 632.95042

Bibliotecário(a) responsável: Euzébio Luiz Pinto CRB-6/3317

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APPROVED: July 26, 2025.

Assent:

Jhersyka da Silva Paes
Author

Marcelo Coutinho Picanco
Adviser

ACKNOWLEDGMENTS

I would like to thank, first and foremost, my parents, Sonia and Esly, for their unconditional love, constant support, and for providing me with all the necessary conditions throughout this journey.

To my sisters, Stefany and Krisley, for their constant affection, friendship, and encouragement.

To my friends Letícia and Damaris, for their presence, companionship, and unwavering support, which made this journey easier and more special.

To Professor Marcelo Picanço, for his dedicated guidance, friendship, valuable advice, and the trust he placed in me, as well as the inspiration he has always conveyed throughout these years.

To my colleagues at the Integrated Pest Management Laboratory, for their time together, friendship, and opportunities for learning and collaboration.

To the examining committee, for their availability, contributions, and suggestions that enriched this work. To the Federal University of Viçosa, for the opportunity to pursue my graduate studies, and to the Graduate Program in Plant Science, for its academic and administrative support. I also express my gratitude to the program secretariat, faculty, coordinators, and staff at UFV, whose work ensures the essential conditions for university life.

This work has been sponsored by the following Brazilian research agencies: Coordination for the Improvement of Higher Education Personnel (CAPES; Financing code 001), Minas Gerais State Foundation for Research Aid (FAPEMIG) and National Council of Scientific and Technological Development (CNPq).

I would like to thank the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) to granting the scholarship.

ABSTRACT

PAES, Jhersyka da Silva, D.Sc., Universidade Federal de Viçosa, July, 2025. **Artificial intelligence tools for projecting failures in tomato leafminer control by insecticides**. Adviser: Marcelo Coutinho Picanco.

The tomato leafminer, Phthorimaea absoluta (Meyrick), represents a major threat to tomato crops in several regions worldwide, with frequent reports of chemical control failures. Thus, the overall objective was to understand the global spatial patterns and these insecticide control failures, using artificial intelligence tools, and to identify the environmental factors associated with their occurrence in Brazil. To this end, a systematic meta-analysis, enhanced by active machine learning, was developed to map the occurrence of P. absoluta control failures by different insecticide chemical groups over the last 64 years. The analysis revealed that avermectins, spinosyns, pyrroles, and isoxazolines had low failure rates (<14%), while diamides, organophosphates, oxadiazines, pyrethroids, and Bacillus thuringiensis had high failure rates. It should be noted that, in regions where product use was more intense and prolonged, pest resistance increased more rapidly. Benzylureas and nereistoxin analogues, despite historical failures, have demonstrated efficacy in recent years, possibly due to biological costs associated with resistance. In the second part, the MaxEnt (Maximum Entropy) model, a machine learning algorithm, was applied to spatially predict the risk of insecticide control failures in Brazil, considering the main biomes. Environmental surveys and georeferenced records of failures were conducted with three chemical groups (benzylureas, diamides, and pyrethroids). The results indicated that the risk of failures due to benzylureas and pyrethroids is higher in the Cerrado and Atlantic Forest biomes, with annual occurrence as the main associated variable. Failures with diamides were more frequent in the Caatinga, Cerrado, and Atlantic Forest, with temperature seasonality as a determining factor. Artificial intelligence tools, such as automated meta-analysis and ecological niche models, have proven effective in systematizing global and regional data, contributing to the development of sustainable resistance management strategies.

Keywords: *Phthorimaea absoluta*; Spatial distribution; MaxEnt

RESUMO

PAES, Jhersyka da Silva, D.Sc., Universidade Federal de Viçosa, julho de 2025. Ferramentas de inteligência artificial para projeção de falhas no controle da traça-do-tomateiro por inseticidas
. Orientador: Marcelo Coutinho Picanco.

A traça-do-tomateiro, Phthorimaea absolute (Meyrick), representa uma grande ameaça à cultura do tomateiro em diversas regiões do mundo, com relatos frequentes de falhas no controle químico. Assim, o objetivo geral foi compreender os padrões espaciais globais e essas falhas no controle de inseticidas, utilizando ferramentas de inteligência artificial, e identificar os fatores ambientais associados à sua ocorrência no Brasil. Para isso, uma meta-análise sistemática, aprimorada por aprendizado de máquina ativo, foi desenvolvida para mapear a ocorrência de falhas no controle por diferentes grupos químicos de inseticidas nos últimos 64 anos. A análise revelou que avermectinas, espinosinas, pirróis e isoxazolinas apresentaram baixas taxas de falha (<14%), enquanto diamidas, organofosforados, oxadiazinas, piretróides e Bacillus thuringiensis apresentaram altas taxas de falha. Ressalta-se que, em regiões onde o uso do produto foi mais intenso e prolongado, a resistência da praga aumentou mais rapidamente. Benzilureias e análogos de nereistoxina, apesar das falhas históricas, demonstraram eficácia nos últimos anos, possivelmente devido aos custos biológicos associados à resistência. Na segunda parte, o modelo MaxEnt (Entropia Máxima), um algoritmo de aprendizado de máquina, foi aplicado para predizer espacialmente o risco de falhas no controle de inseticidas no Brasil, considerando os principais biomas. Levantamentos ambientais e registros georreferenciados de falhas foram conduzidos com três grupos químicos (benzilureias, diamidas e piretróides). Os resultados indicaram que o risco de falhas devido a benzilureias e piretróides é maior nos biomas Cerrado e Mata Atlântica. Falhas com diamidas foram mais frequentes na Caatinga, Cerrado e Mata Atlântica. Ferramentas de inteligência artificial, como meta-análises automatizadas e modelos de nicho ecológico, têm se mostrado eficazes na sistematização de dados globais e regionais, contribuindo para o desenvolvimento de estratégias sustentáveis de manejo da resistência.

Palavras-chave: *Phthorimaea absoluta*; Distribuição espacial; MaxEnt

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GENERAL INTRODUTION

The tomato leafminer *Phthorimaea absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is considered the most important pest in tomato crops in several regions of the world (Santana Jr. et al., 2019; Choudhary et al., 2022). Its attack can cause crop losses of up to 100% (Bacci et al., 2019a; Desneux et al., 2022). This pest is native from South America at the Peruvian Andes region, and it was reported in Brazil since the early 1980s (Tropea et al., 2012; Campos et al., 2017; Azrag et al., 2023). Subsequently, this insect has been spreading throughout the main tomato-producing regions worldwide. (Santana et al., 2019; Azrag et al., 2023). Its larvae build mines and bore into branches, flowers, and fruits which compromise photosynthesis, reducing plant growth, and yield losses (Guedes & Picanço, 2012; Guedes et al., 2019; Balzan & Moonen, 2021). Its control is primarily achieved through insecticides application (Guedes and Siqueira, 2012; Desneux et al., 2022). In tomato crops, an average of 12 insecticide applications are made, although up to 36 applications can take place (Bacci et al., 2019a; Zamora et al., 2020). In certain crops, failures in insecticide control of *P. absoluta* have been observed (Roditakis et al., 2018; Desneux et al., 2022).

Control failures occur when insecticides fail to achieve the desired pest control efficiency (Guedes, 2017). Their main causes are the selection of insecticide-resistant pest populations and pesticide application technology issues (Guedes, 2017). Factors that influence insecticide pest control failures include environmental variables, insecticide chemicals groups, their duration of use, and control efficiency at the beginning of pesticide adoption (Silva et al., 2011; Gontijo et al., 2013; Guedes, 2017). These variables can affect insect population dynamics, plant development, and insecticide efficiency (Bacci et al., 2019; Barros et al., 2015; Jędrszczyk et al., 2016; Maliszewska & Tęgowska, 2017). They shapepest density in crops, as impact insect survival, growth, development, reproduction, and behavior (Martins et al., 2016; Cocco et al., 2015). Also, it determines the frequency of insecticide application (Gagic et al., 2021) and the voltinism (Martins et al., 2016), which regulates the insecticide-resistant pest populations selection (Rosenheimi & Tabashnik, 1990).

Artificial intelligence (AI) is a field of science and technology that studies and develops systems capable of simulating intelligent behaviors (Nilsson, 1988; Russell & Norvig, 2016). It is employed to develop systems that require humans to execute and solving everyday duties (Garg, 2021). Its advantages include faster task completion than a human expert, rapid execution of difficult tasks, high success rates, and the discovery of unexplored topics (Khanzode & Sarode, 2020). Within AI, there is Machine Learning as a subfield (Talwar & Kumar, 2013). It involves the development of algorithms that learn from data without programming (Talwar & Kumar, 2013). This technique has been used in agriculture to determine adverse factors in crops and to make estimates (Bernardes et al., 2022; Santos et al., 2025).

Prediction models in agriculture are essential tools for forecasting phenomena (Bakhtadze et al., 2021). These models are tools that display results to assess potential occurrences of a phenomenon and answer the "what if" question (Wit & Vries, 1985). Recently, several studies have focused on developing prediction models to understand potential population distribution in relation to variations in previously established factors. This knowledge is crucial for determining short- and long-term management strategies to *P. absoluta* (Choudhary et al., 2019).

Despite of the wide reports about *P. absoluta* control failures in major tomato-producing regions, this phenomenon remains understudied. Figure out how these records happens across the world, as well as the studies that underlie them, is crucial. Furthermore, identifying regions at risk of developing control failures is essential for determining insect management strategies. Thus, the objective of this thesis was to determine the risk of failures in *P. absoluta* control by insecticides in Brazilian biomes using the MaxEnt machine learning algorithm. Besides that, an artificial intelligence-assisted meta-analysis was performed on the global assessment of failures in *P. absoluta* control by insecticides.

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CHAPTER 1: Meta-analysis aided by artificial intelligence on the global assessment of control failures of *Phthorimaea absoluta* by insecticide

Abstract

Phthorimaea absoluta (Lepidoptera: Gelechiidae) is the key pest in tomato crops at several regions of the world. Chemical control is the main method of *P. absoluta* manage, although lack of control have been observed. In this study, a systematic review was carried out, using meta-analysis and artificial intelligence to evaluate the global control failures of *P. absoluta* by different groups of insecticides in the last 64 years of the pest's dispersion around the world. Avermectins, spinosyns, pyrroles and isoxazolines showed low pest control failure rates (up to 14%). *Bacillus thuringiensis* has shown low pest control efficiencies over the years. Diamides, organophosphates, oxadiazines, and pyrethroids were initially efficient but over the years of adoption began to fail into controlling this Lepidoptera. The analogues of nereistoxins and benzoylureas were initially efficient and with their broadly use, it starts to present control failures, but recently it returned to showing control efficiency. The frequency of observation and time demanded to verify pest control failures were greater in South America, than in Europe, Africa, and Asia. There has been a high occurrence of failures in the control of *P. absoluta* by insecticides over the years, with variations among continents and chemical groups. Avermectins, spinosyns, and pyrroles had low failure rates. Benzoylureas and nereistoxin analogues have presented recovery on efficacy. Isoxazoline still has no records of control failures. Finnaly, diamides, organophosphates, oxadiazines, *B. thuringiensis* and pyrethroids continue to present failures.

Keywords: tomato leafminer, insecticide resistance, global spread of pest, chemical groups of insecticides.

1. INTRODUCTION

Phthorimaea absoluta (Meyrick) (= *Tuta absoluta*) (Lepidoptera: Gelechiidae) is considered the most important pest in tomato crops in several regions of the world (Santana Jr. et al., 2019; Choudhary et al., 2022). *P. absoluta* is native to South America, the Peruvian Andes, and was found in Brazil in the beginning of 1980s (Tropea et al, 2012; Campos et al., 2017; Azrag et al., 2023). Since then, this insect has been spreading throughout the main tomato producing regions of the world and it has been causing major losses on tomato crop by its high destructive capability (Santana et al., 2019; Azrag et al., 2023). The caterpillar impact tomato plant productivity due to its leafmining habit, which reduces photosynthesis (Miranda et al., 1998; Martins et al., 2016). Also, *P. absoluta* reduce plant growth because its larvae pierce the shoot apex. Furthermore, its larvae cause flower abortion and fruit sprouting (Guedes et al., 2019; Hogea, 2020). Then, this pest can cause losses of up to 100% on tomato production (Kabylova et al., 2021; Choudhary et al., 2022).

The use of insecticides is the most efficient and widely used tool for controlling *P. absolute* in tomato crops (Guedes & Picanço, 2012; Gontijo et al., 2013). To minimize the damage caused by this pest, tomato growers apply insecticides frequently. In some situations, the number of applications can exceed 36 per season (Guedes & Picanço, 2012; Aynalem, 2022).

However, insecticide application does not always achieve the desired control efficiency, resulting in control failures. Pest control failures refer to situations in which the applied pesticide do not cause the target of pest mortality (Gontijo et al., 2013; Silva et al., 2011; Guedes, 2017; Choudhary et al., 2022). One of the main reasons for this low control efficiency is the selection of pest resistant populations to insecticides (Siqueira et al., 2000; Silva et al., 2011) and application technology issues (Paixão, 2021).

The increase of pesticide application, dose, improper use of mixtures, and substitution by a more toxic pesticides are consequences of leafminer control failure which generates ecological, economic, and toxicological problems (Yuan et al., 2024). Then, failure of insecticides to control *P. absoluta* has become one of the world's major threats in tomato production.

There is a large volume of studies that report the efficiency rate of insecticides used to control *P. absoluta*. The use of meta-analysis makes it possible to use this data to determine the control failures of *P. absoluta* over the years around the world.

With the use of artificial intelligence (AI) tools, it is possible to interactively apply natural language processing and automatic active learning (ML) models, thus reducing the effort involved in the systematic review (Paul & Barari, 2023; Page et al., 2023). In interactive ML procedures, the researcher interacts with an ML model in a loop and based on the researcher's decisions (training dataset with relevant studies versus irrelevant studies), the model updates its predictions for the remaining dataset, selecting the next study that is presented to the researcher. The researcher then analyzes this study and gives it a label (i.e. relevant or irrelevant). The newly labeled study is added to the training dataset and another round is iterated (Van de Schoot et al., 2021; Ferdinands et al., 2023). Interactive ML minimizes the number of studies to be selected by the researcher, prioritizing articles that are more likely to be relevant.

Despite the importance of *P. absoluta* and its efficient control, to date, there is not a global study investigatingthe control failures of this pest by several groups of insecticides. Therefore, the aim of this work was to carry out a systematic review of the literature aided by AI to recognize global spatial and temporal evaluations of the occurrence of control failures of *P. absoluta* by different groups of insecticides over the last 64 years. Through meta-analysis, we quantitatively assessed the control failures of the main insecticide groups against the tomato leafminer. This allowed us to systematically analyze the state of the art in insecticide use for *P. absoluta* control and identify global failures in controlling this pest with insecticides from various chemical groups.

2. MATERIALS AND METHODS

This study systematically reviewed the literature on control failures and the global spread of *Phthorimaea absoluta*.

2.1. Pest control failures around the world

For the systematic literature review carried out in this study, the guidelines described in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) were used (Moher et al., 2009; Ferdinands et al., 2023). These guidelines include the stages of identification, screening, eligibility, and inclusion.

2.1.1. Identification

To identify published studies about the control of *Phthorimaea absoluta* by insecticides at a world perspective, searches were carried out on Google Scholar, Scopus (Elsevier), and Web of Science (Clarivate Analytics) databases. The title, abstract or keywords of the manuscript were selected for the search words. The search heuristic was defined as: ("*Tuta absoluta*" OR "*Scrobipalpula absoluta*" OR "*Scrobipalpa absoluta*" "*Gnorimoschema absoluta*" OR "*Scrobipalpuloides absoluta*" OR "*Phthorimaea absoluta*" OR "Tomato moth" OR "tomato moth" OR "Tomato leafminer" OR "South American tomato moth") AND (Mortality OR “Inefficient product" OR "control failure" OR efficiency OR "resistant population" OR "toxicity") AND (pesticides OR agrochemical* OR insecticide* OR pesticide* OR agrochemical* OR pesticide* OR insecticide*). The title, authors, abstract, journal, year of publication and digital object identifier (DOI) were obtained from the selected papers. Duplicated studies found in the database were removed manually based on the matching of titles and DOI.

2.1.2. Screening

Machine Learning (ML) based text classification was used to screen titles and abstracts. Using the open-source tool with active learning techniques ASReview (Van de Schoot et al., 2021). To perform this, a training dataset was built by labeling the studies to build the model. The training dataset consisted of 16 irrelevant papers and 22 relevant papers. The title and abstracts of the articles were standardized (converted to lowercase) and processed into matrices using the inverse term frequency method (Van de Schoot et al., 2021; Bernardes et al., 2022). The Naive Bayes algorithm, a classification algorithm with good performance for text (Wahyudi, 2022), was applied to calculate relevance scores for the articles published according to the tool. The review after 57 successive non-relevant articles was interrupted in the learning cycle, and the result of the process included 125 relevant published articles.

2.1.3. Eligibility

The full text of the articles selected after screening was assessed for eligibility. Eligible articles were those reporting the evaluation of trials using one or more groups of insecticides to control *P. absoluta* larvae. These were peer-reviewed, with a description of the response variable evaluated, rigorous study design with controls, dose of the active ingredient, year of data collection, and the location where *P. absoluta* population was tested.

2.1.4. Inclusion

From the papers selected after check the full text, information was systematically extracted for qualitative analysis based on the topics defined (Supplementary Table). Finally, through the qualitative analysis, only trials that evaluated the groups avermectin, *B. thuringiensis*, diamides, benzoylureas, isoxazolines, nereistoxins, organosphosphates, oxadiazines, pyrethroids, pyrroles, and spinosyns were considered for the meta-analyses.

2.2. Global spread of *P. absoluta*

This section of the study aimed to determine the time interval between the introduction of *Phthorimaea absoluta* in various regions of the world and the subsequent occurrence of pest control failures. In order to determine the global spread of *P. absoluta* over the years, the introduction date of this insect was registered for each country. This data was obtained from literature and Global Biodiversity Information Facility online database (GBIF, 2024). These records were filtered using the *thin* function of the *spThin* R package (Aiello-Lammens et al. 2019). Through this procedure, only one record was kept every 10 km, reducing spatial autocorrelation (Liu & Zurita-Milla, 2022).

2.3. Data analysis

All the analyses were carried out by meta (Balduzzi et al., 2019) and stats packages in the R software (version 4.1.3) (R Core Team, 2021). From the records of *P. absoluta* introductions in different parts of the world, a global dispersion map of this insect over the years was performed.

The mortality data of *P. absoluta* by insecticides was organized according to pesticide chemical groups (IRAC, 2024a). When the mortality caused by the insecticide was equal to or greater than 80%, the product was considered efficient in controlling the pest. When mortality was less than 80%, pest control was considered to have failed. It was adopted because 80% is the minimum mortality for an insecticide to be considered efficient in Brazil (IRAC-Brasil, 2024).

For each continent in the world, a graph about the occurrence or non-occurrence of *P. absoluta* control failure by insecticides from each chemical group over the years was built. These graphs also show the introduction year of the insect to that continent for determining the time interval between the introduction and the subsequent occurrence of *P. absoluta* control failures on that region.

The percentages of *P. absoluta* control failures by each chemical group of insecticides were calculated using formula (1).

(1) $PCF_{ij} = (100 \times NCF_{ij}) \div TN_{ij}$, where: PCF = percentage of control failures; i = continent (1 = Americas, 2 = Europe; Africa and 3 = Asia); j = chemical group of the insecticide; NCF = number of control failures e TN = total number of tests.

The times (mean ± range) for the first observation of *P. absoluta* control failures by insecticides from different chemical groups were calculated using formula (2).

(2) $\overline{TCC} = [\sum(YCF_{ij} - YIP_{i})] \div N_{ij}$, where: $\overline{TCC}$ = average time (years) to observe control failures; i = continent (1 = Americas, 2 = Europe; Africa and 3 = Asia); j = chemical group of the insecticide; YCF = year of observation of control failure; YIP = year the pest was introduced to the continent e N = number of tests. The lower and upper limits of this variable were the time (years) of observation of the first and last control failure on the continent by the chemical group of insecticides, respectively.

3. RESULTS

In the stage of identifying the literature to evaluate global control failures of *Phthorimaea absoluta* by insecticides, 675 articles published in the databases were found. After removing duplicates, 588 articles on this subject were identified. Sorting by active machine learning (ML) selected 38 labeled studies (16 irrelevant and 22 relevant) for the model. Active learning cycles were run until 57 irrelevant studies were found in sequence. This screened out 125 relevant studies. In the eligibility stage, 13 studies that did not report and/or describe the subject and object of interest were removed. In the inclusion stage, 112 studies (=1322 independent trials) were used for the qualitative analysis. For the quantitative analysis, 92 studies (=952 independent trials) were selected which evaluated at least one of the 11 main chemical groups of insecticides for the control of *P. absoluta* (Figure 1).

Figure 2 shows the spread of *P. absoluta* over the years to the present day. This insect occurs in open fields in 128 countries in the Americas, Africa, Europe, and Asia. *P. absoluta* is native from South America and it was described in 1917. In the 1970s, occurred its first wave of expansion throughout Chile, Peru, and Brazil. In the 1980s and 1990s, this insect was introduced to the rest of South America. Subsequently, *P.*

absoluta was introduced in the 2010s in Central America and North America. *P. absoluta* second wave of expansion began in 2006, with its introduction into Europe (Spain) and for two decades this insect has been dispersing across the European, African, and Asian continents (Figure 2).

Figure 3 shows the toxicity tests of insecticide groups on *P. absoluta*. There are 11 groups of insecticides evaluated for the control of *P. absoluta*. Diamides are the group of insecticides with the highest number of published trials (312 trials) (Figure 1A). The number of trials has increased over the decades. However, there was an impressive increase in the execution/publication of trials in the 2010s, corresponding to 960 independent trials. Europe (35%) and America (34%) are the continents with the highest number of insecticide toxicity trials on *P. absoluta*. On the other hand, 19% and 13% of insecticide toxicity trials on *P. absoluta* took place on the Asian and African continents, respectively. From the 1970s to the 1990s, insecticide toxicity tests on *P. absoluta* were carried out exclusively in countries of the American continent. In the 2000s, in addition to the Americas (97 trials), trials began in Europe (14), Africa (5) and, Asia (1). In the 2010s, the continent that contributed the most insecticide toxicity trials for *P. absoluta* was Europe (411 trials), followed by the Americas (206 trials), Asia (203 trials) and Africa (141). In the 2020s to date, there have been 165 trials in total, the Americas (58 trials), Asia (46 trials), Europe (37 trials) and Africa (24 trials).

In the Americas, insecticide toxicity tests on *P. absoluta* began to be carried out in 1976 involving the organophosphate group. This was 10 years after the pest was reported in Argentina. From the first report of the pest in Brazil 1979, the other insecticide groups began to be tested to assess *P. absoluta* mortality. In the trials carried out in the Americas, avermectins, spinosyns, and pyrroles have always been effective. Isoxazolines, on the other hand, are the most recently used group of insecticides (2020s) to control of *P. absoluta* and they have been effective. Trials carried out with *Bacilus thuringiensis* report that this bacterium has not been effective in controlling *P. absoluta*. At the beginning of their use in the 2000s, insecticides from the diamide group were effective against *P. absoluta*. However, across the time, many cases of low *P. absoluta* control efficiency by diamides have been reported. The use of pyrethroids to control *P. absoluta* began in the 1970s with high control efficiency. However, over the years there have been many records of pest control failures using pyrethroids. The use of insecticides from the benzoylurea group also began in the 1990s with high control efficiency. From the 2000s onwards, several cases of pest control failures using benzoylureas were reported. However, from the 2020s onwards there have been records of efficient control of the pest by benzoylureas. The use of insecticides from the group of nereistoxin analogues began in the 1980s with high control efficiency. From the late 1990s to the early 2010s, many cases of pest control failures by nereitoxin analogues were reported. However, from the 2020s onwards there have been records of efficient control of the pest by nereistoxin analogues. For the other groups of insecticides (organophosphates and oxadiazines), there are records of both efficiency and control failures of *P. absoluta* in different places and years (Figure 4).

In Europe, control failures have been reported for the main insecticide groups with failures in the Americas since the pest began to spread on the continent in 2006 (Figure 4). On the African continent, two years after the introduction of the pest (2010), the insecticide groups with recorded failures in the Americas and Europe also showed initial records of control failures (*B. thuringiensis*, growth regulators, nereistoxin analogues, organophosphate). The groups that were effective in the Americas and Europe were also effective on the African continent (avermectins and spinosyns). In Asia, the groups with control failures on the other continents showed control failures at the beginning of their use (Figure 5).

Figure 6 shows the percentage of trials with control failures on the continents for the 11 insecticide groups used to control *P. absoluta*. Avermectins, spinosyns, and isoxalines show low percentages (up to 13.79%) of trials with control failures for *P. absoluta* on all continents. On the other hand, *B. thuringiensis*, diamides, growth regulators, and pyrethroids reported high percentages of control failure (up to 100%) for *P. absoluta* on all continents. The organophosphate group shows a high percentage (up to 100%) of control failure on three continents (the Americas, Europe and Africa). Insecticides from the pyrrole and oxadiazine groups showed a high percentage of pest control failure (up to 77.80%) on the African and European continents, respectively (Figure 6).

Figure 7 shows the time taken for the insecticides groups fail to control *P. absoluta* worldwide. On the American continent, the times ($\bar{x}$ = 13,92 years) for the first *P. absoluta* control failures to be reported by the insecticide groups than in the other continents ($\bar{x}$ = 5,75 years). In Europe, Africa, and Asia, insecticides taken on average 5.75, 6.93, and 4.58 years to notice control failure, respectively.

4. DISCUSSION

The considerable amount of insecticides toxicity tests (1322) over the years when *Phthorimaea absoluta* populations were dispersing around the world is due to the relevance of leafminer and the requirement to control it. Another fact that contributed to the large number of research on this subject is the rapid dispersion of *P. absoluta* across the American continent countries (which is its region of origin), Europe (as of 2006), Africa (as of 2008) and Asia (as of 2009) (Urbaneja et al., 2007; Boualem et al., 2012; Al-Jboory et al., 2012; Santana et al., 2019). Furthermore, the rapid selection of pest populations resistant to insecticides means that there is a constant demand to carry out research to select efficient products to control them in regions where the pest is present (Sawadogo et al., 2020; IRAC, 2024).

According to insecticides efficiency against *P. absoluta* over the years of spray, they can be splitted into four groups. The first group are composed by insecticides that showed low rates of failure to control the pest over the years. In the second group, there are insecticides that have always failed to control the pest. In the third group are the insecticides that were initially efficient and over the years of use began to show failures in controlling the pest. In the fourth group are the insecticides that were initially efficient and with their use began to show failures in controlling the pest but recently have returned to perform efficiency in their control.

Avermectins, spinosyns, pyrroles and isoxazolines belong to the group of insecticides with low pest control failure rates (up to 13.79% failures). Avermectins, spinosyns, pyrroles, and isoxazolines were registered for use in the control of *P. absoluta* in 1985, 1995, 1989, and 2023. One of the reasons why avermectins, spinosyns, and pyrroles have shown effective control against *P. absoluta* over the years is the low frequency of these insecticides use to control this pest (Barros et al., 2015; Silva et al., 2016). It reduces the selection pressure for insecticide-resistant pest populations over the years (Berger et al., 2016). Isoxazolines belong to a new group of insecticides (IRAC group 30) and the first product in this group (isocycloseram) was registered in 2023 for use in controlling *P. absoluta*. This insecticide has shown high efficiency in controlling *P. absoluta* (up to 100%) and has been applied frequently (at least once a week) to control the pest in tomato crops. Therefore, it is expected that with this intense use, populations of *P. absoluta* resistant to this insecticide will be selected over the years.

In the group of products that over the years have shown low pest control efficiency is the entomopathogenic bacterium *B. thuringiensis*. These products penetrate the insects' body orally and act in the digestive system as microbial disruptors of the mesenteric membrane (Sharaby & El-Bendary, 2017). To control the pest, the insect must ingest plant tissue containing the bacteria's spores (Ruiu, 2015). As *P. absoluta* larvae are found inside leaves, fruits and stems (Miranda, 1998; Martins et al., 2016), the ingestion of plant tissue with spores of the bacteria is possibly low, which explains the low control efficiencies of the plague by these products. Furthermore, the concentrations used of these products are generally low to obtain high insect mortalities (van der Linden and van der Staaii, 2010; Silva et al., 2011; Roby and Hussein, 2019).

Diamides, organophosphates, oxadiazines and pyrethroids are among the group of insecticides that were initially efficient and over the years began to fail to control the pest. This was possibly due to the high efficiency of these products at the beginning of their use and the high frequency of their applications (Guedes, 2017). At the beginning of their use, diamides and pyrethroids in particular were highly efficient (>90%) in controlling *P. absoluta* (Haji et al., 1986; Ragaei al., 2013). These high efficiencies have led to the intense use (applications at least once a week) of these insecticides to control *P. absoluta*. High frequency of use and high insect mortality are factors in the selection of insecticide-resistant pest populations (Bielza et al., 2016). The low susceptibility of *P. absoluta* after the selection of populations resistant to diamides, organophosphates, oxadiazines and pyrethroids must be related to the biological costs of these resistances. This resistance may or may not have a biological cost. In situations where there is no biological cost, susceptible and resistant insects have similar biological performance (Campos et al., 2015; Guedes, 2017). Thus, after insecticides are discontinued due to their low efficacy, there is no new selection of insect populations that are susceptible to these products (Guedes & Picanço, 2012; Guedes et al., 2019).

Analogues of nereistoxins and benzoylureas are among the group of insecticides that were initially efficient and, with their use, began to fail to control the pest, but which have returned to control efficiency in recent years. This was possibly due to the selection of insect populations resistant to them and in recent times there has been selection of pest populations susceptible to them (Shehzad et al., 2023; Siddiqui et al., 2023). Among the selection factors for insecticide-resistant populations are the frequency of applications, pressure and intensity of selection (Onstad & Knolhoff, 2023, Thia et al., 2023). The recent selection of *P. absoluta* populations susceptible to nereistoxin and benzoylurea analogues must be related to the biological costs of these resistances. In situations where there is a biological cost, susceptible insects perform better biologically than resistant ones (Gul et al., 2023). Thus, after insecticides are discontinued due to their low efficacy, there is no selection of insect populations susceptible to these products (Belinato & Martins, 2016; Gassmann, 2023).

The percentages of *P. absoluta* control failures and the time taken to detect these failures varied between the continents of the world and the insecticide groups. In this context, it was found that in South America (the insect's region of origin) it took longer for control failures to be detected for *P. absoluta* than on the other continents. On the other hand, at the beginning of the introduction of *P. absoluta* in Europe, Africa and Asia, pest control failures were already detected for insecticides from the benzoylurea, diamide, and oxadiazine groups. This is possibly due to the climatic differences in these regions and the genetic characteristics of the insect populations (Martins et al., 2016; Silva et al., 2011; Santana et al., 2019). Populations of *P. absoluta* are favored by hot and dry weather, therefore, in regions and seasons with these climatic conditions their females produce a greater number of eggs and these insects have a substancial number of generations per year (Martins et al., 2016). The production of a greater number of eggs per female and a greater number of generations per year leads to a faster selection of insecticide-resistant populations of the pest (Jacomb & Holman, 2016; Onstad & Knolhoff, 2023). Santana Jr. et al. (2019) determined the regions of the world with the greatest ecoclimatic suitability for *P. absoluta*. Therefore, it is expected that in regions with greater ecoclimatic suitability, insecticide-resistant populations of this pest will be selected more intensely and quickly. The fact that control failures were detected for insecticides from the groups of benzoylureas, diamides and oxadiazines in the initial period of introduction of *P. absoluta* was possibly due to the migrating populations of this insect already possessing genes that conferred resistance to these insecticides (Tonnang et al. al., 2015, Siqueira et al., 2000, Roditakis et al., 2013b).

5. CONCLUSIONS

In conclusion, a large number of failures to control *P. absoluta* with insecticides have been reported. These failures varied between the world's continents and insecticide groups. Avermectins, spinosyns and pyrroles have shown low control failure rates over the years. Benzoylureas, diamides, organophosphates, oxadiazines, pyrethroids, and nereistoxin analogues after years of use failed to control the pest. For diamides, organophosphates, oxadiazines, and pyrethroids these failures persist to the present time. Benzoylureas and nereistoxin analogues have once again shown effective pest control in recent times. The frequency of observation and time to verify pest control failures were greater in South America, the region of origin of the pest, than in Europe, Africa and Asia.

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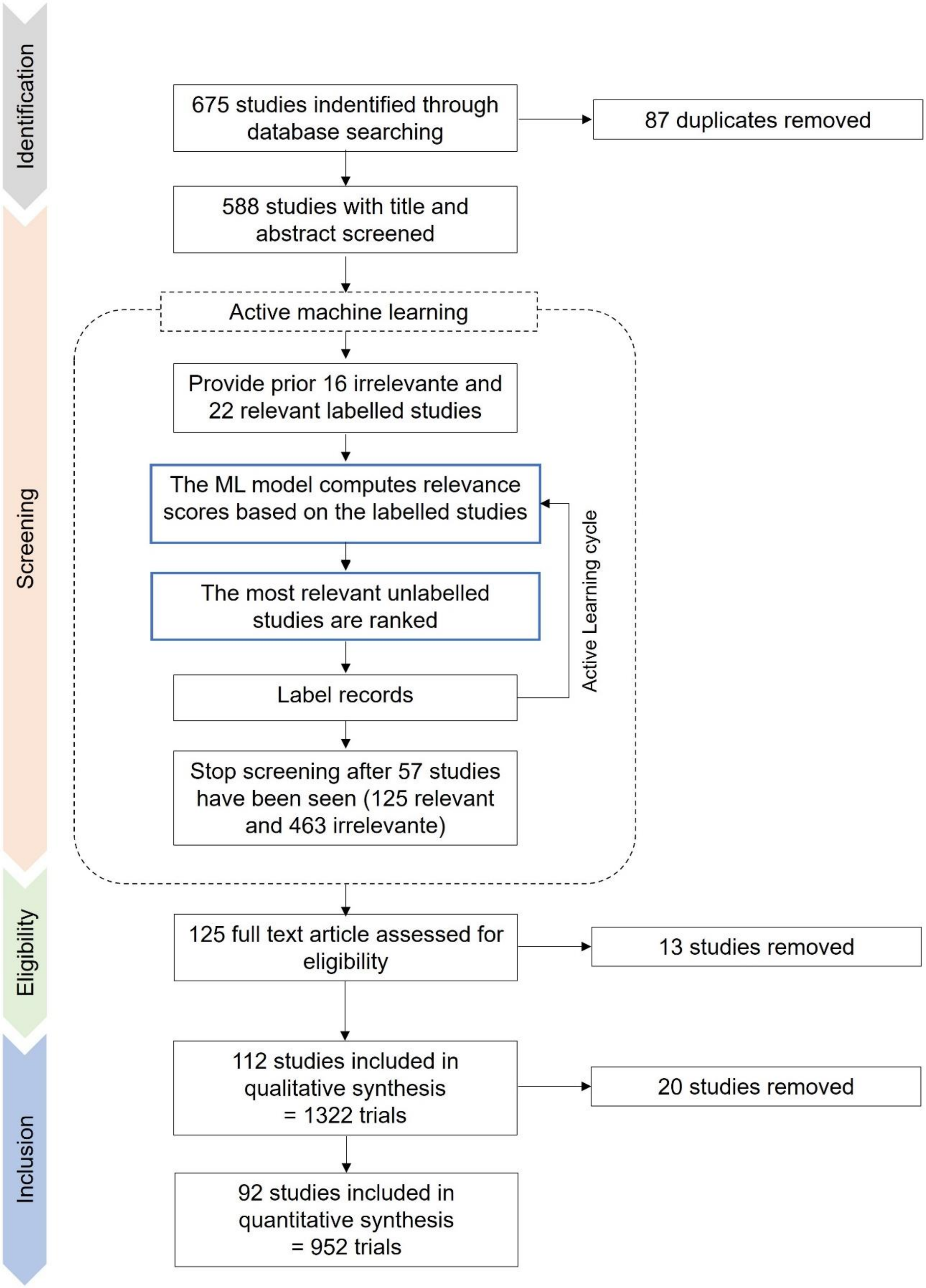

Figure 1. Flowchart of identification, screening, eligibility and inclusion of the systematic literature review on the assessment of global control failures of *Phthorimaea absoluta* by insecticides using active machine learning (ML).

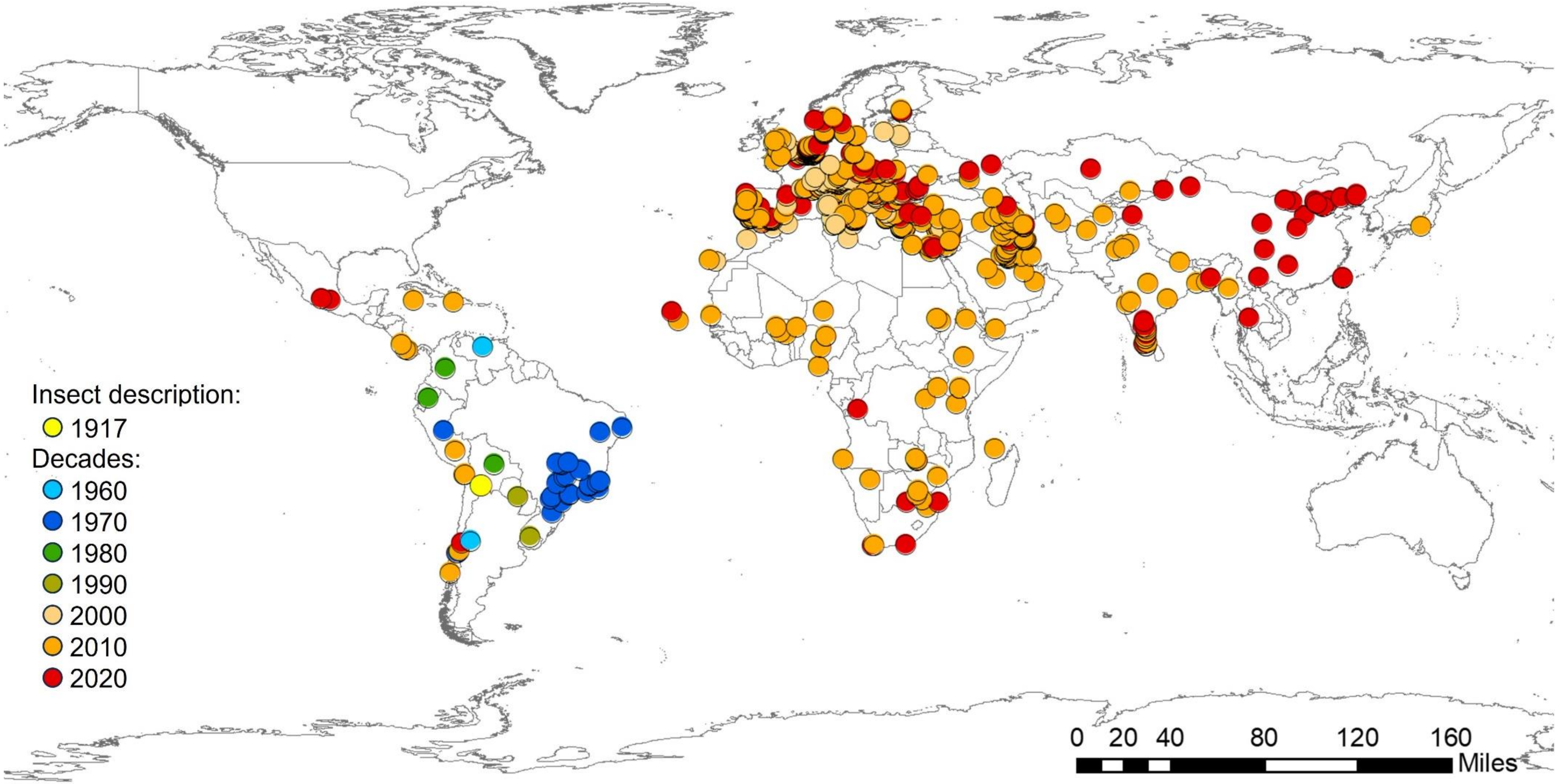

Figure 2. Dispersion of *Phthorimaea absoluta* in the world from 1960 to 2024.

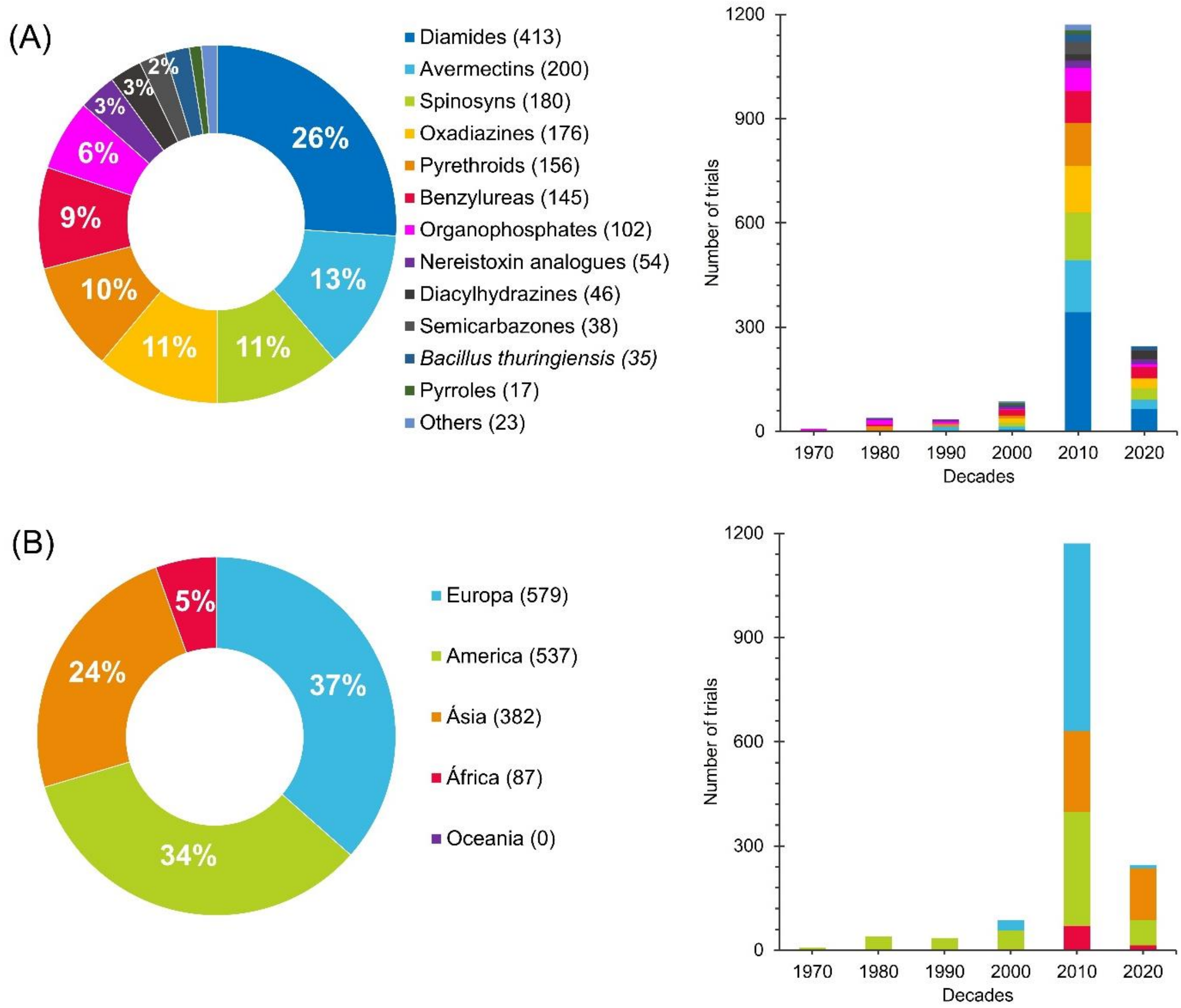

Figure 3. Toxicity tests of (A) groups of insecticides to *Phthorimaea absoluta* on (B) continents of the world from the 1960s to 2020.

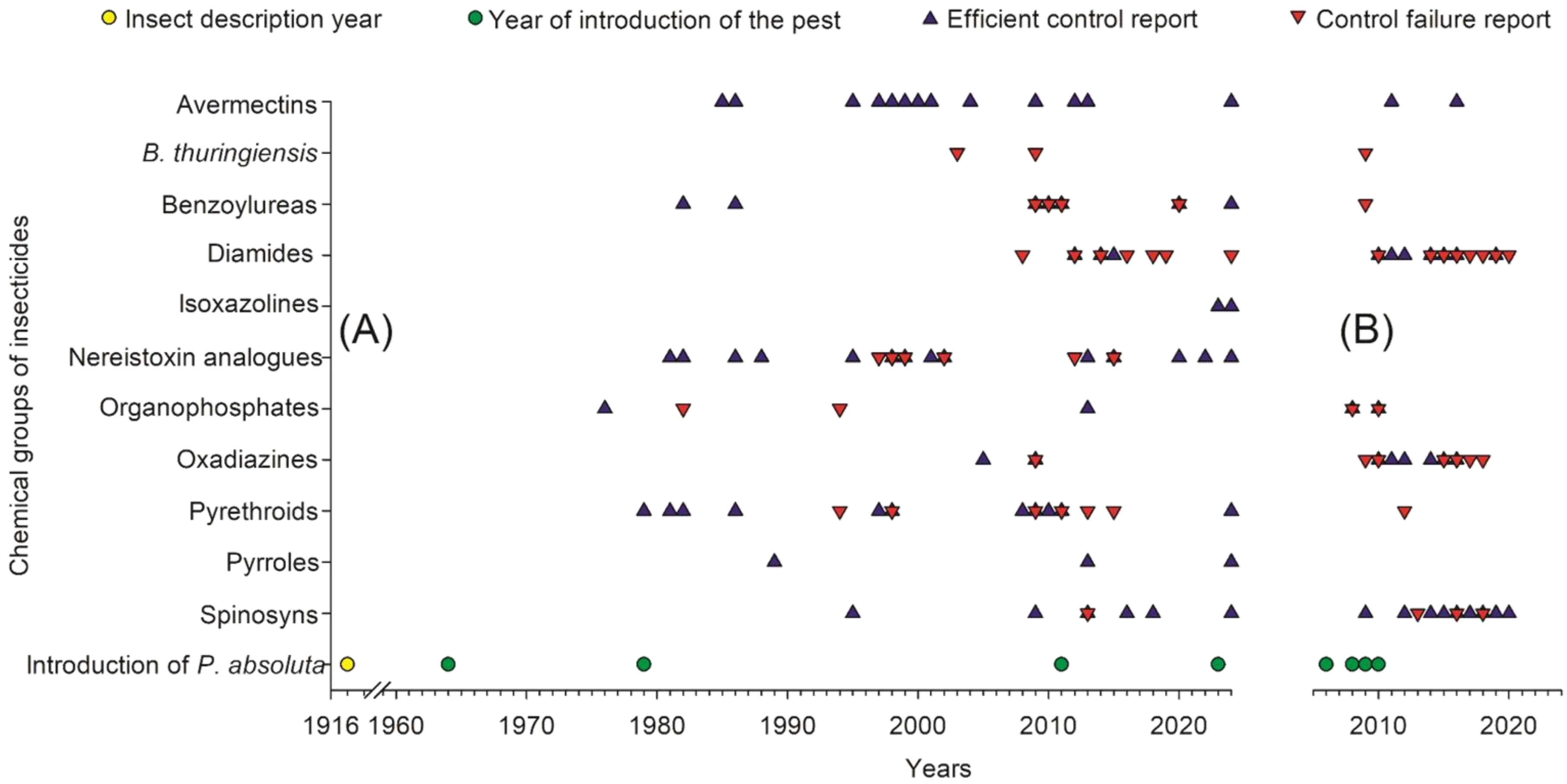

Figure 4. Introduction of *Phthorimaea absoluta*, history of use and control failures of this pest by insecticides from different groups in (A) America and (B) Europe.

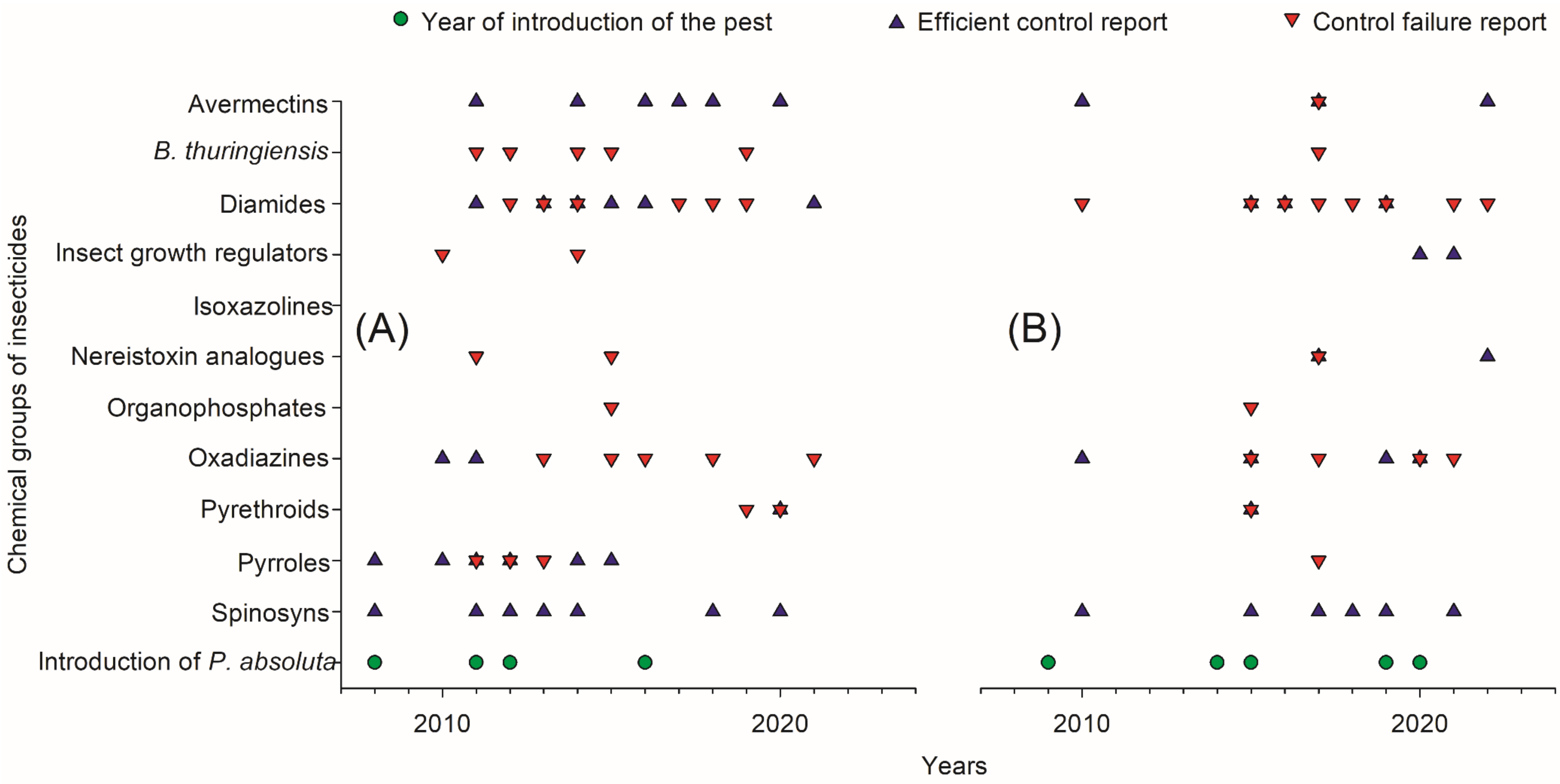

Figure 5. Introduction of *Phthorimaea absoluta*, history of use and control failures of this pest by insecticides from different groups in (A) Africa and (B) Asia.

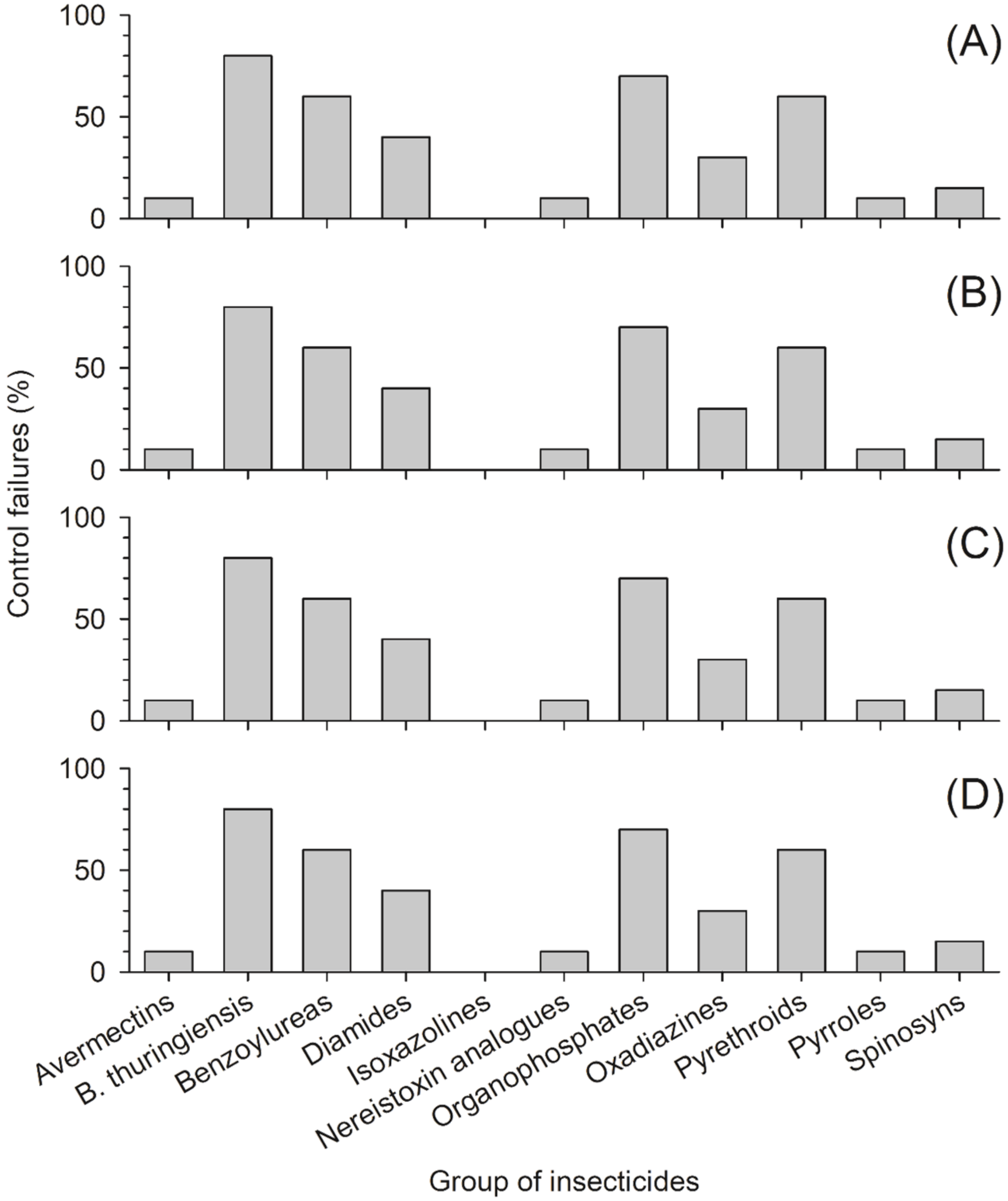

Figure 6. Percentage of failures in the control of *Phthorimaea absoluta* by insecticides from the main groups used for its control in (A) Americas, (B) Europe, (C) Africa and (D) Asia.

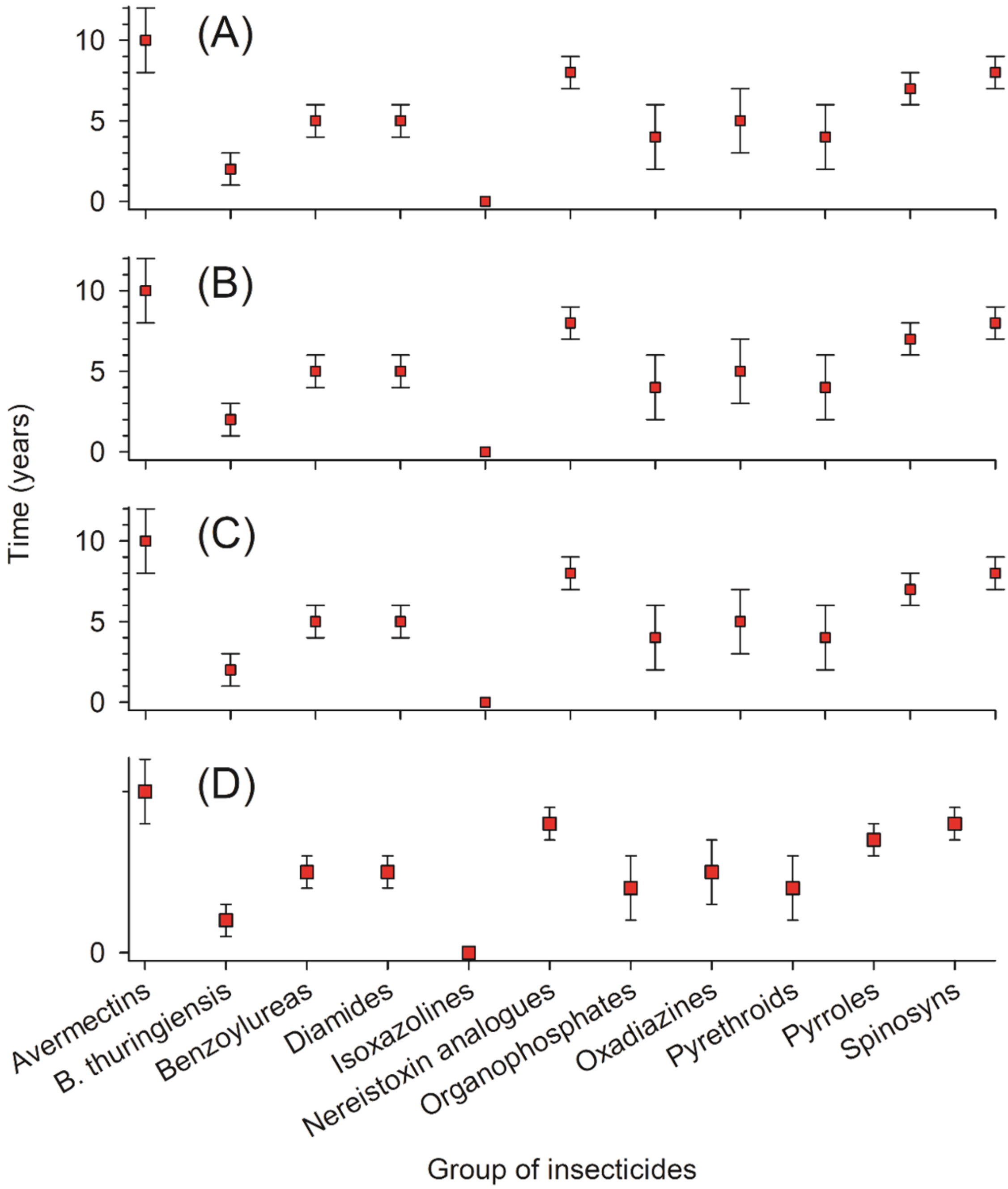

Figure 7. Time (mean ± variation range) for the occurrence of control failures of *Phthorimaea absoluta* by insecticides from different groups in (A) Americas, (B) Europe, (C) Africa and (D) Asia.

CHAPTER 2: Spatial distribution and environmental variables associated with control failures of *Phthorimaea absoluta* by insecticides determined by machine learning algorithm

Abstract

For pest control to be sustainable, the methods applied must be efficient and have a low environmental impact. Pest control failures bring economic and environmental problems. *Phthorimaea absoluta* is the main pest in tomato crops worldwide. Benzoylureas, diamides, and pyrethroids are among the insecticides with the highest reports of pest control failures, and Brazil is the country where this has been most observed. Machine learning models are suitable for predicting biological events. Thus, this study aimed to determine the risks of failures in the control of *P. absoluta* by insecticides in Brazilian biomes using the MaxEnt machine learning algorithm. The risks of pest control failures by benzoylureas and pyrethroids were higher in tomato crops located in the Cerrado and Atlantic Forest biomes, and annual precipitation was the critical variable associated with these failures. The risks of control failures by diamides were higher in crops located in the Caatinga, Cerrado and Atlantic Forest, and temperature seasonality was the critical variable associated with these failures. In conclusion, the models determined in the study are robust to predict the regions with higher risks of *P. absoluta* control failures by insecticides and they indicated the environmental variables associated with these risks.

Key words: corn leafhopper, decision-making, sampling cost, sampling time, negative binomial.

1. INTRODUCTION

For pest control in crops to be sustainable, the methods applied must be efficient and have a low environmental impact. Failure to control the methods applied can result in major losses due to damage caused by pests and environmental problems due to the excessive application of inefficient control methods in an attempt to control these organisms (Rauf, 2024).

The tomato leafminer *Phthorimaea absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is the main pest in tomato crops worldwide and its attack can cause losses of up to 100% (Bacci et al., 2019a; Han et al., 2019). Its control is mainly done by insecticides (Desneux et al., 2022; Guedes and Siqueira, 2012). At a tomato crop season, an average of 12 insecticide applications are made, but this number could increase to 36 36 applications in case of high pest pressure (Bacci et al., 2019a; Zamora et al., 2020). Failures of *P. absoluta* control by insecticides have been observed in tomato crops (Desneux et al., 2022; Roditakis et al., 2018). These failures occur when the insecticides applied do not achieve the desired efficiency in controlling the pest (Gontijo et al., 2013; Silva et al., 2011; Guedes, 2017; Choudhary et al., 2022). The main reasons for these control failures are the selection of pest populations resistant to insecticides and application technology issues (Guedes, 2017; Gontijo et al., 2013). Brazil is the country where failures in the control of *P. absoluta* by insecticides have been reported most frequently. Among these pesticides, insecticides from benzoylureas, diamides, and pyrethroids groups present highest occurrence of this phenomenon (Guedes et al., 2019; Silva et al., 2021).

Environmental variables shape the occurrence of pest control failures by insecticides. (Guedes, 2017; Gontijo et al., 2013; Silva et al., 2011). These variables can affect insect population dynamics, plant development, and insecticide efficiency (Bacci et al., 2019b, 2021; Barros et al., 2015; Jędrszczyk et al., 2016; Maliszewska and Tęgowska, 2017). Environmental variables affect pest density in crops because they impactinsect survival, growth, development, reproduction, and behavior (Bacci et al., 2021; Martins et al., 2016; Cocco et al., 2015). These variables affect the frequency of insecticide application (Gagic et al., 2021) and the number of generations of the insect per year (Martins et al., 2016) what influences the selection of insecticide-resistant pest populations (Rosenheimi and Tabashnik, 1990).

Studies of the spatial distribution of control failure risks make it possible to determine the regions where they occur and the environmental variables related to them. The maximum entropy ecological niche model (MaxEnt) is a machine learning algorithm that uses environmental variables to determine the spatial distribution of species and biological phenomena (Martyushev and Seleznev, 2006; Ou et al. 2024; Pascariu et al., 2019; Ponti and Sannolo, 2023, Waldrip et al., 2015). These determinations are useful for understanding the factors regulating insect control failures by different groups of insecticides and for establishing strategies for managing pest resistance to these pesticides. Despite the importance of *P. absoluta*, no studies have been conducted to date on the spatial distribution of the risks of control failures of this pest by insecticides. Therefore, this study aimed to determine the spatial distribution risk of *P. absoluta* control failures by pesticides and environmental variables in Brazilian biomes by MaxEnt machine learning algorithm.

2. MATERIAL AND METHODS

The work was carried out in three stages. In the first, data were collected. In the second, models were determined and validated. Finally, spatial distributions projections of failures control risks were made.

2.1. Data collection

2.1.1. Spatial distribution of tomato crops

Production data (t) of tomato crops were collected for each municipality in Brazil in the last year with available data (2022) (IBGE, 2024). The areas (km^2) of each municipality were also collected (IBGE, 2023).

2.1.2. Spatial distribution of control failure records

Data on *P. absoluta* control failures with insecticides from the benzolurea, diamide and pyrethroid groups in Brazil were obtained from scientific publications, reports and databases. Searches were conducted on the Web of Science, Science Direct, Google Scholar, PubMed and Arthropod Pesticide Resistance Database. Pest control failure was considered to have occurred when the recommended dose of the insecticide caused mortality of less than 80% (Gontijo et al., 2013; Guedes, 2017; Silva et al., 2011). A total of 53, 59 and 71 points of records of pest control failures by benzolureas, diamides and pyrethroids were collected, respectively. The control failure recording points were georeferenced (Figura 1).

2.2. Spatial distribution models of control failures

2.2.1. Selection of model variables

Initial models were determined using MaxEnt software (version 3.4.4), 20 variables obtained from WorldClim version 2.1 (http://www.worldclim.org/) with a spatial resolution of 2.5 arc-min (5 km) and the occurrence points of control failures about each group of insecticides. For each model, the percentage contribution of each 20 variables to the model was determined (Ponti and Sannolo, 2023). Subsequently, collinearity between the variables was analyzed. Thus, Pearson's correlation coefficient between the variables was calculated using *SDMtoolbox 2.5* from *ArcGis* software (Brown, 2020). Among the variables that presented a correlation coefficient greater than 0.7, the one that presented the highest percentage contribution to the initial model was selected (Reis et al., 2025).

2.2.2. Model configuration selection

Thirty models were determined for each group of insecticides. In these determinations, the k-fold randomized cross-validation method of the Ecological Niche Model Evaluation (ENMeval) package in R software version 4.2.3 was used (Kass et al., 2020). In these determinations, the previously selected variables and 10,000 background points were used. The features of class linear, quadratic, hinge, product and threshold and regularization multiplier values from 1 to 5 were tested. For each group of insecticides, the model with settings that presented the lowest value for the Akaike Information Criterion (AIC) was selected. This was applied because models with lower AIC values have high predictive capacity and smaller size (Akaike, 1998; Mandrekar, 2010). Variation curves of the risks of pest control failures were determined as a function of the model variables. The average value of the other variables was used in these determinations (Mahatara et al., 2021).

2.2.3. Model validation

The models were validated by calculating the area under the curve (AUC) and by checking the insertion of the pest control failure record points in areas classified by the models as having a high risk of this phenomenon occurring. Initially, a receiver operating characteristic (ROC) was determined for each model. Subsequently, a ten-fold cross-validation of each ROC was performed to determine the AUC of each model (Allouche et al., 2006; Schartel and Cao, 2024).

2.3. Projections of spatial distributions

2.3.1. Tomato crops and control failure records

Based on the production data and the areas of tomato crops, the tomato production index was calculated for each municipality using the formula (1).

(1) $TPi = PRi \div ARi$, where: TP = tomato production index (t km^{-2}), PR = tomato production in the municipality (t), AR = area of the municipality (km^2) and i = municipality in Brazil. A map of the spatial distribution of tomato crops in the Brazilian biomes and the points where pest control failures were recorded for each insecticide group was created using ArcGIS software (Brown, 2020). On the maps, areas were classified as having low, medium, and high tomato production when they presented the TP index < 0.05 t km^{-2}, $0.05 \leq TP \leq 10$ t km^{-2} and TP 10 t km^{-2}, respectively.

2.3.2. Risks of pest control failures in biomes

Using the model for each group of insecticides, the risks of pest control failures in the areas of the Brazilian biomes were determined. For this purpose, the ecoclimatic suitability index was used. This index varies from 0 to 1 in the final maps. When it has a value equal to 0, the area is unsuitable for the phenomenon to occur. When it has a value equal to 1, the area has the maximum probability of the phenomenon occurring (Mahatara et al., 2021). This probability was categorized into three interpretative categories using the Logistic Limit of Maximum Test Sensitivity Plus Specificity (MTSPS). Areas were classified as low risk when this index was less than 0.2, medium risk when the index had values between 0.2 and 0.6, and high risk when the index had a value greater than 0.6. A map with risks of pest control failures for each group of insecticides was created using these indexes and the ArcGIS software (Pimpler, 2017).

2.3.3. Risks of control failures in tomato producing regions

In this part of the work, the areas with medium and high (>0.05 t km^{-2}) tomato production were intersected with the areas with high risks of control failures. This was done using the ArcToolbox – Analysis Tools – Intersect tool of the ArcGis software (Pimpler, 2017). Subsequently, the percentage of tomato crop areas with risks of control failures was determined using formula (2).

(2) $PR_{jz} = 100 \times AR_j \div BA_z$, , where: PR = percentage of tomato crop areas at risk of control failures, AR = area (km^2) of tomato crops at risk of control failures, BA = area

(km^2) of the biome with tomato crops, *j* = biome (1 = Amazon forest, 2 = Cerrado, 3 = Caatinga, 4 = Tropical wetlands, 5 = Atlantic forest e 6 = Lowland plains) e *z* = group of insecticides (1 = benzoylureas, 2 = diamides and 3 = pyrethroids).

3. RESULTS

3.1. Spatial distribution of tomato crops and occurrences of pest control failures

It was found that tomato crops are grown in all Brazilian biomes. They are mainly located in the Cerrado, Atlantic Forest, and Caatinga biomes. The areas with tomato crops in the Amazon, Tropical wetlands and Lowland plains are smaller (Figure 1). In Brazil, 53, 59, and 71 records of failures in controlling *P. absoluta* with insecticides from the benzoylureas, diamides, and pyrethroids groups, respectively, were reported. These control failures were observed for populations of *P. absoluta* from tomato crops grown in the Caatinga, Cerrado, Atlantic Forest, and Lowland plains biomes (Figura 1).

3.2. Spatial distribution models of control failure risks

Annual precipitation (41.4% contribution to the model), mean temperature of the coldest quarter (25.9%), temperature annual range (22.9%) and elevation of the site (9.8%) were the variables of the final model of spatial distribution of the risks of occurrence of control failures of *P. absoluta* by benzoylureas. The best configuration of this model used the combination of hinge, linear, and quadratic (LQH) resource classes and a regulation multiplier equal to one. This configuration was selected because it presented the lowest value for the Akaike information criterion (AIC = 407.46) (Table 3). This final model presented an area under the curve (AUC) of 0.996 ± 0.004 (Figure 2A).

3.2.2. Model of control failures by diamides

Temperature seasonality (79.6% contribution to the model), elevation (11.3%), temperature annual range (22.9%), and precipitation of warmest quarter (3.2%) were the variables in the final spatial risks distribution occurrence model of *P. absoluta* control failures by diamides. The configuration elected for this model used the combination of linear and quadratic resource classes (LQ) and a regulation multiplier equal to one. This setting was selected because it presented the lowest AIC value

(536.90) for the model (Table 1). This final model presented AUC = 0.967 ± 0.008 (Figure 2B).

3.2.3. Model of control failures by pyrethroids

Annual precipitation (56.9% contribution to the model), mean temperature of the coldest quarter (21.1%), temperature annual range (11.3%), precipitation of coldest quarter (4.6%), elevation (4.2%), and precipitation of warmest quarter (1.9%) were the variables of the final spatial distribution occurrence risks model of *P. absoluta* control failures by pyrethroids. The configuration selected for this model used the combination of linear, quadratic, hinge, and product (LQHP) resource classes and a regulation multiplier equal to two. This setting was selected because it presented the lowest AIC value (547.92) (Table 1). This final model presented AUC = 0.994 ± 0.006 (Figure 2C).

3.3. Effect of environmental variables on the risk of control failures

In locations with temperature annual range less than 18°C, mean temperature of coldest quarter between 18 and 25°C, annual precipitation between 860 and 1500 mm and altitude to 1040 m, the risk of pest control failures by benzoylureas was higher (Figure 3A). In locations with temperature seasonality less than 10%, temperature annual range of less than 15°C, precipitation of warmest quarter less than 210 mm, and elevation between 710 and 1350 m, the risk of pest control failures by diamides was higher (Figure 3B).

In places with temperature annual range of less than 20%, mean temperature of coldest quarter between 10 and 20°C, Annual precipitation of 850 to 2100 mm, precipitation of warmest quarter below 1000 mm, precipitation of coldest quarter of 70 to 600 mm and elevation of 1500 m down, the risks of failures in pest control by pyrethroids were greater (Figure 3C).

3.4. Spatial distribution of pest control failure risks in Brazil

It was found that 10.20%, 5.42%, and 84.38% of the areas in Brazil presented respectively high, medium, and low risks of pest control failures due to benzoylrrheas. The regions with the highest risk of control failures due to benzoylureas were in the Atlantic Forest, Cerrado, Caatinga, and coastal strip of the Lowland plain's biomes (Figure 4A). It was observed that 11.73%, 32.38%, and 55.89% of the areas in Brazil presented respectively high, medium and low risks of control failures due to diamides.

The regions with the highest risk of control failures due to diamides were in the Caatinga, Cerrado, north-central Amazon, and Atlantic Forest (Figure 4B). Meanwhile, 13.94%, 4.45%, and 55.89% of the Brazilian area presented respectively high, medium and low risks of pest control failures by pyrethroids. The regions with the highest risk of these failures were located in the Atlantic Forest, Cerrado, Caatinga, and coastal Lowland plains (Figure 4C).

3.5. Risks of control failures in tomato producing regions

In 32.27%, 47.07%, and 41.09% of the areas with tomato crops, there was a risk of pest control failures by benzoylureas, diamides, and pyrethroids, respectively (Figure 5). The tomato-producing regions with a risk of control failures by benzoylureas were located in the Cerrado (11.87% of the area with tomato crops), Atlantic Forest (10.87%), Caatinga (9.01%) and Lowland plains (0.52%) biomes (Figure 5A). The tomato-producing regions with a risk of control failures by diamides were in the Caatinga (17.89%), Cerrado (12.33%), Atlantic Forest (10.29%) Amazon (5.46%), and Lowland plains (1.10%) (Figure 5B). The tomato-producing regions at risk of control failures due to pyrethroids were located in the Atlantic Forest (16.21%), Cerrado (14.94%), Caatinga (8.83%), and Lowland plains (1.10%) (Figure 5C).

4. DISCUSSION

The spatial distribution of records of failures in the control of *P. absoluta* by insecticides from the benzoylureas, diamides, and pyrethroids groups in different locations in Brazilian biomes indicates that these phenomena are associated with environmental factors in these locations. The spatial distribution models of the risk of *P. absoluta* control failures by benzoylureas, diamides and pyrethroids proved to be adequate to predict these phenomena. This can be demonstrated by their high values for the area under the curves (AUC > 0.96). Since models with AUC > 0.90 have high predictive capacity (Janssens and Martens, 2020; Vanderlooy and Hüllermeier, 2008). Control failures records are in areas where the models predicted these fails demonstratings the robustness of the models. Another relevant characteristic of the models is their simplicity (Venne and Currie, 2021). This can be noticed by few variables at the models and their settings present the lowest values for the Akaike information criterion (AIC). Models with lower AIC values combine high predictive capacity and smaller size (Cavanaugh and Neath, 2019). The fact that the size and location of areas at risk of pest control failures varied depending on the insecticide group and among Brazilian biomes has implications for the management of pest resistance to insecticides (Li, et al., 2020).

This indicates that distinct variables were associated with these processes. In this context, the spatial distribution models of control failures by benzylureas and diamides had four variables, while the model for pyrethroids had six variables. Furthermore, there are regions where tomatoes are not yet grown in Brazil that present suitable characteristics for control failures, since the size of the areas at risk of control failures was larger than tomato crops areas.

Temperature seasonality was the variable that most affected control failures by diamides. The regions with the lowest air temperature v showed the greatest risk of *P. absoluta* control failures by diamides occurred. This variable may influence the selection of *P. absoluta* populations resistant to diamides because of air temperature on pest density and tomato crops.

In situations of higher pest densities, the frequency of insecticide applications increases (Gagic et al., 2021), which affects the selection of populations resistant to these products (Roditakis et al., 2009). The biological performance of *P. absoluta* is shaped by air temperature. Since the optimal temperature for *P. absoluta* is 30 °C (Martins et al., 2016), in situations of low or very high temperatures, the biological performance of *P. absoluta* is downregulated, and consequently its densities in crops decrease. Locations and seasons with extreme air temperatures are unsuitable for growing tomato crops (Shamshiri et al., 2018). In regions with mild temperatures, up to three tomato crops can be grown per year (Okali and Sumberg, 2012).

In regions with year-round tomato crops, the number of generations of the pest is greater and consequently the selection of pest populations resistant to insecticides will be greater (Rosenheimi and Tabashnik, 1990). It was found that the variation in annual precipitation was the variable that most affected the risk of failures in pest control by benzoylureas and pyrethroids. In regions with medium rainfall, there were higher risks of failures in controlling *P. absoluta* by insecticides from these two groups. Elevated rainfall has impared *P. absoluta* populations because the mechanical impact of its drops causes mortality of eggs and larvae and increases the action of entomopathogenic fungi (Bacci et al., 2019a, 2019b, 2021). On the other hand, poor humidity decrease insect populations because it is essential for the survival, growth, development, and reproduction of these organisms (Buxton, 1932). Thus, in situations of adequate rainfall, the densities of *P. absoluta* are higher, and consequently the selection of pest populations resistant to insecticides will be greater.

In higher risk of *P. absoluta* control failures regions best practices of integrated pest management most be applied to avoid pest's resistance to insecticides (Guedes, 2017, Onstad and Knolhoff, 2023, Silva et al., 2011, Venkatesan et al., 2022). It was observed that the largest areas at risk of failure of *P. absoluta* control by benzoylureas and pyrethroids occurred in tomato crops located in the Atlantic Forest and Cerrado biomes. The areas with the greatest risk of failure of control by diamides occurred in the Caatinga and Cerrado biomes. This management program should use practices that minimize the selection of *P. absoluta* populations resistant to insecticides.

These include the adoption of a decision-making system and other control methods, especially biological and cultural. Also, explore the insecticide selectivity, resistance monitoring, adjuvants, correct insecticides doses, and rotation of products with different modes of action (Onstad and Knolhoff, 2023; Venkatesan et al., 2022). The predictions made by the models determined in this work can be used to carry out efficient and sustainable control of *P. absoluta* in tomato crops. This is because these predictions can be used to prevent control failures and manage pest resistance to insecticides.

In conclusion, the models determined in this study are robust to predict the regions with the highest risk of *P. absoluta* control failures by insecticides and they indicate the environmental variables associated with these risks. The risks of pest control failures by insecticides from the benzoylureas and pyrethroids groups were higher in tomato crops located in the Cerrado and Atlantic Forest biomes, and annual precipitation was the critical variable associated with these failures. The risks of control failures by diamides were higher in crops located in the Caatinga, Cerrado and, Atlantic Forest biomes, and temperature seasonality was the critical variable associated with these failures.

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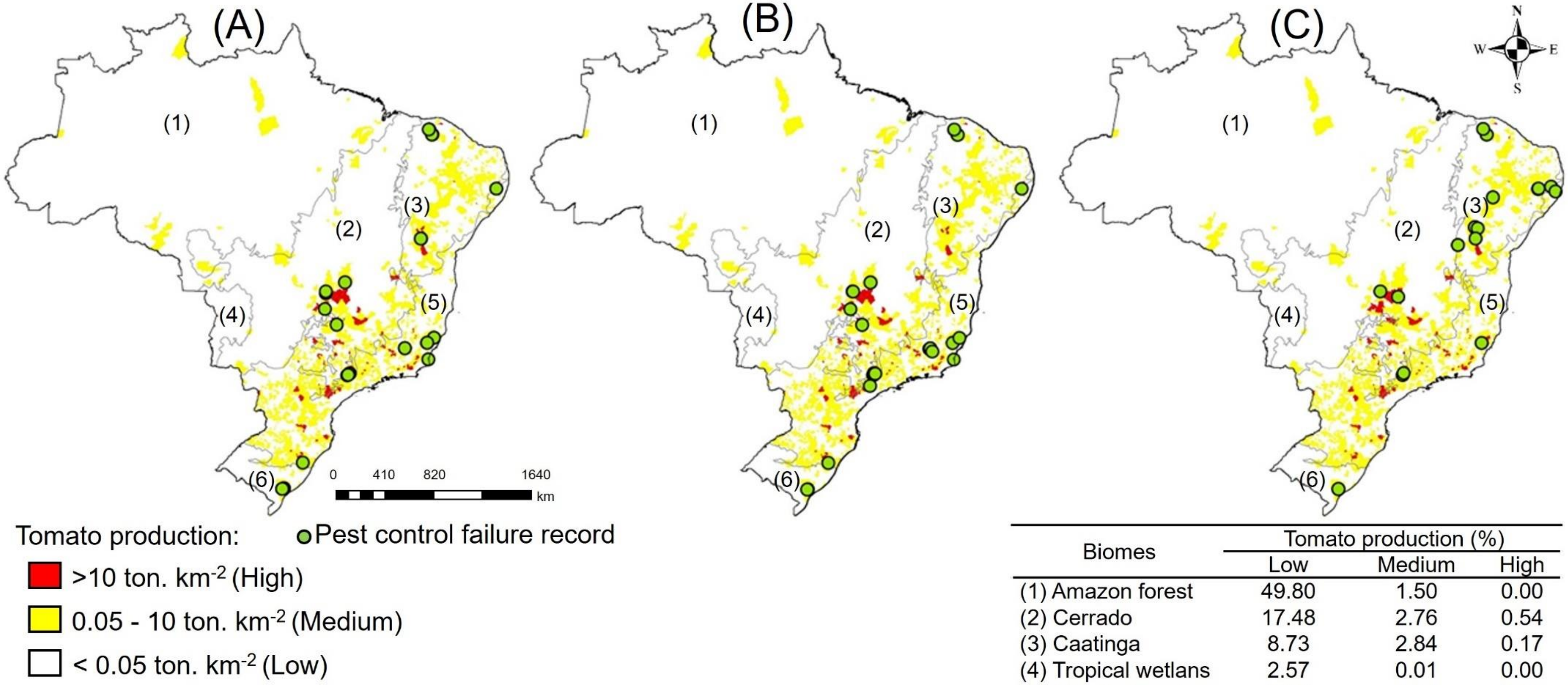


Biomes	Tomato production (%)		
	Low	Medium	High
(1) Amazon forest	49.80	1.50	0.00
(2) Cerrado	17.48	2.76	0.54
(3) Caatinga	8.73	2.84	0.17
(4) Tropical wetlans	2.57	0.01	0.00
(5) Atlantic forest	7.37	4.04	0.35
(6) Lowland plains	1.64	0.19	0.00
Total for Brazil	87.59	11.34	1.06

Figure 1. Location of tomato crops in Brazil and records of occurrence of failures in the control of *Phthorimaea absoluta* by insecticides from the groups of (A) benzoylureas, (B) diamides and (C) pyrethroids.

Table 1. Contribution of environmental variables to the final spatial distribution models in Brazil of the risks of control failures of *Phthorimaea absoluta* by insecticides from the benzoylureas, diamides and pyrethroids groups using the maximum entropy machine learning algorithm (MaxEnt).

Variables		Benzoylureas		Diamides		Pyrethroids	
Code	Name	Variable	Contribution (%)	Variable	Contribution (%)	Variable	Contribution (%)
Bio 4	Temperature seasonality (°C)	Bio 12	41.4	Bio 4	79.6	Bio 12	56.9
Bio 7	Temperature annual range (°C)	Bio 11	25.9	Bio 20	11.3	Bio 11	21.1
Bio 11	Mean temperature of coldest quarter (°C)	Bio 7	22.9	Bio 7	5.9	Bio 7	11.3
Bio 12	Annual precipitation (mm)	Bio 20	9.8	Bio 18	3.2	Bio 19	4.6
Bio 18	Precipitation of warmest quarter (mm)					Bio 20	4.2
Bio 19	Precipitation of coldest quarter (mm)					Bio 18	1.9
Bio 20	Elevation (m)						

Table 2. Selection of the ideal configuration of spatial distribution models in Brazil for the risk of failures in the control of *Phthorimaea absoluta* by insecticides from the benzoylureas, diamides and pyrethroids groups using the Akaike information criterion (AIC).

Benzoylureas				Diamides				Pyrethroids			
Rank	FC	RM	AIC	Rank	FC	RM	AIC	Rank	FC	RM	AIC
1	LQH	1	536.90	1	LQ	1	407.46	1	LQHP	2	547.92
2	LQHP	3	548.72	2	L	1	408.36	2	LQHPT	2	547.92
3	LQHPT	3	548.72	3	LQ	2	409.79	3	H	1	725.49
4	LQHPT	4	551.84	4	LQ	3	410.86	4	H	2	571.81
5	LQ	1	548.32	5	L	2	411.21	5	LQHP	1	587.21
6	LQHP	1	538.16	6	LQ	4	416.23	6	LQHPT	1	587.21
7	LQH	4	549.70	7	LQH	2	416.49	7	LQH	2	561.53
8	H	2	549.71	8	LQH	3	418.35	8	LQ	1	565.10
9	LQH	3	551.14	9	H	2	419.21	9	LQH	3	566.86
10	LQ	2	551.59	10	LQHP	2	419.21	10	LQH	1	572.54
11	LQHP	4	551.84	11	LQH	1	419.24	11	LQ	2	574.02
12	LQ	4	552.43	12	LQH	4	419.94	12	LQH	4	574.82
13	H	3	552.63	13	L	3	420.44	13	H	3	575.08
14	LQ	3	553.48	14	H	3	421.50	14	LQ	3	575.44
15	LQH	5	553.78	15	LQHP	3	421.50	15	H	4	575.77
16	LQ	5	554.94	16	LQHPT	3	421.50	16	LQHP	3	579.82
17	LQHP	5	555.66	17	H	4	421.65	17	LQHPT	3	579.85
18	LQHPT	5	555.66	18	LQHP	4	421.65	18	LQHP	4	582.82
19	H	4	556.12	19	LQHPT	4	421.65	19	LQHPT	4	583.59
20	L	1	556.28	20	LQ	5	422.96	20	LQ	4	584.85
21	L	2	558.01	21	LQHPT	5	423.43	21	LQ	5	586.77
22	L	3	560.73	22	LQHP	5	423.43	22	L	1	587.01
23	LQH	2	561.90	23	H	5	423.43	23	H	5	587.80
24	L	4	564.46	24	LQH	5	424.18	24	L	2	590.06
25	H	5	564.60	25	LQHPT	2	425.66	25	L	3	591.18
26	LQHP	2	565.29	26	L	4	426.06	26	LQHP	5	591.18
27	LQHPT	2	565.29	27	L	5	430.15	27	LQHPT	5	594.03
28	L	5	569.27	28	LQHPT	1	485.46	28	L	4	597.16
29	LQHPT	1	577.01	29	LQHP	1	532.65	29	LQH	5	633.88
30	H	1	545.67	30	H	1	532.65	30	L	5	724.76

RM: regularization multiplier; FC: features; Linear (L), quadratic (Q), product (P), limit (T) and hinge (H).

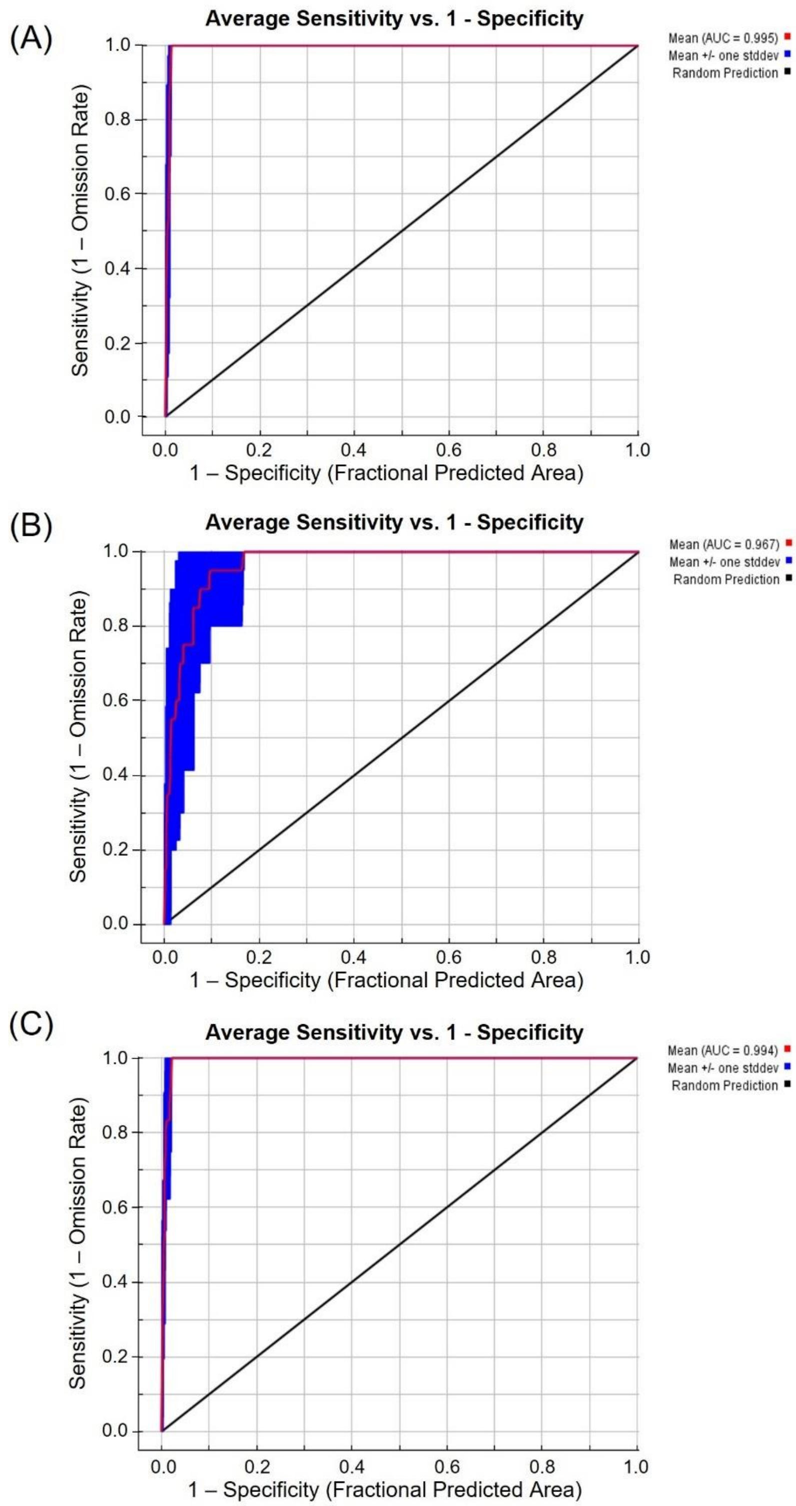


Figure 2. Repeated operating characteristics curves and areas under the curve for the final models of spatial distribution of *Phthorimaea absoluta* control failures by (A) benzoylureas, (B) diamides, (C) pyrethroids using maximum entropy (MaxEnt) machine learning algorithm.

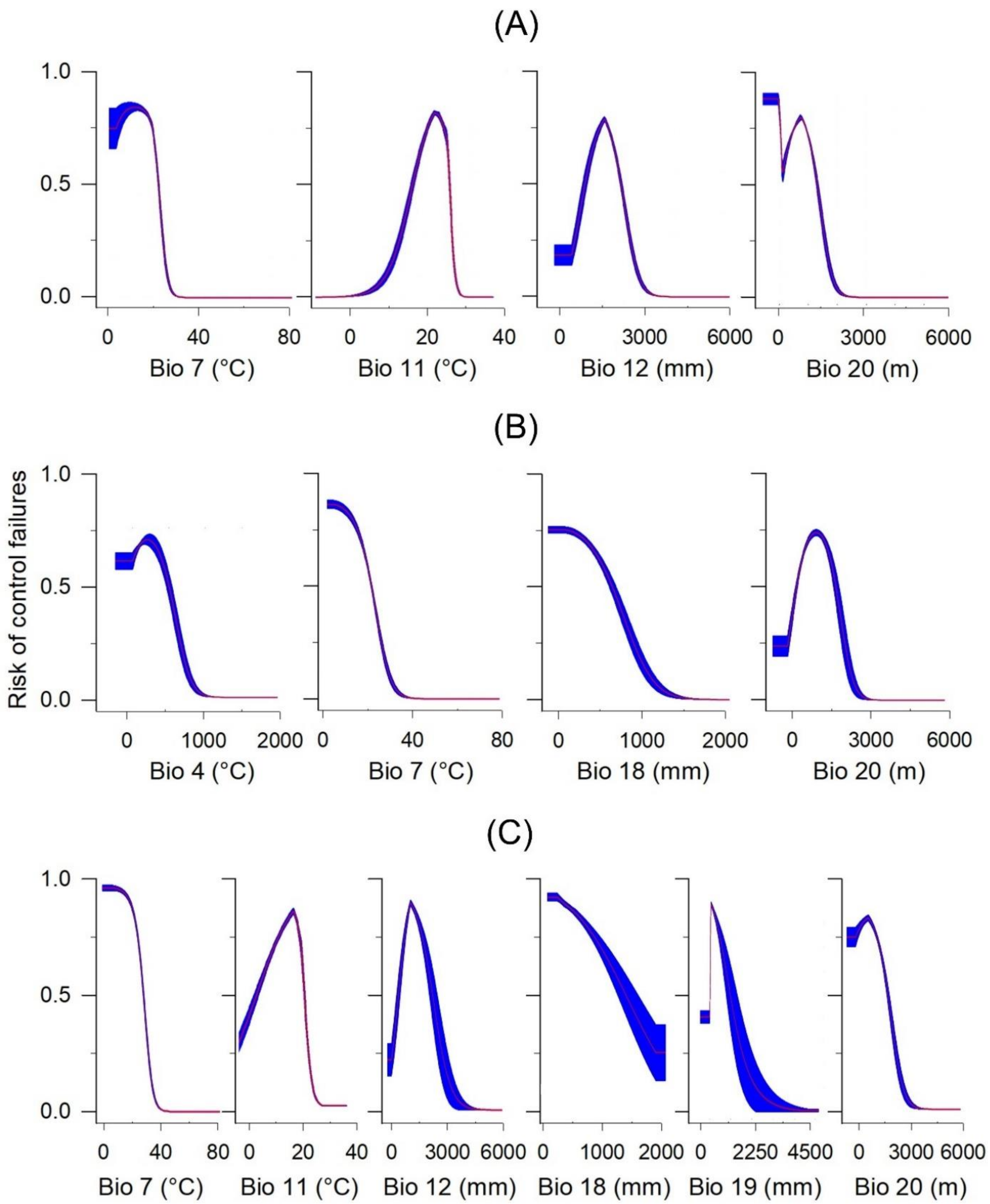
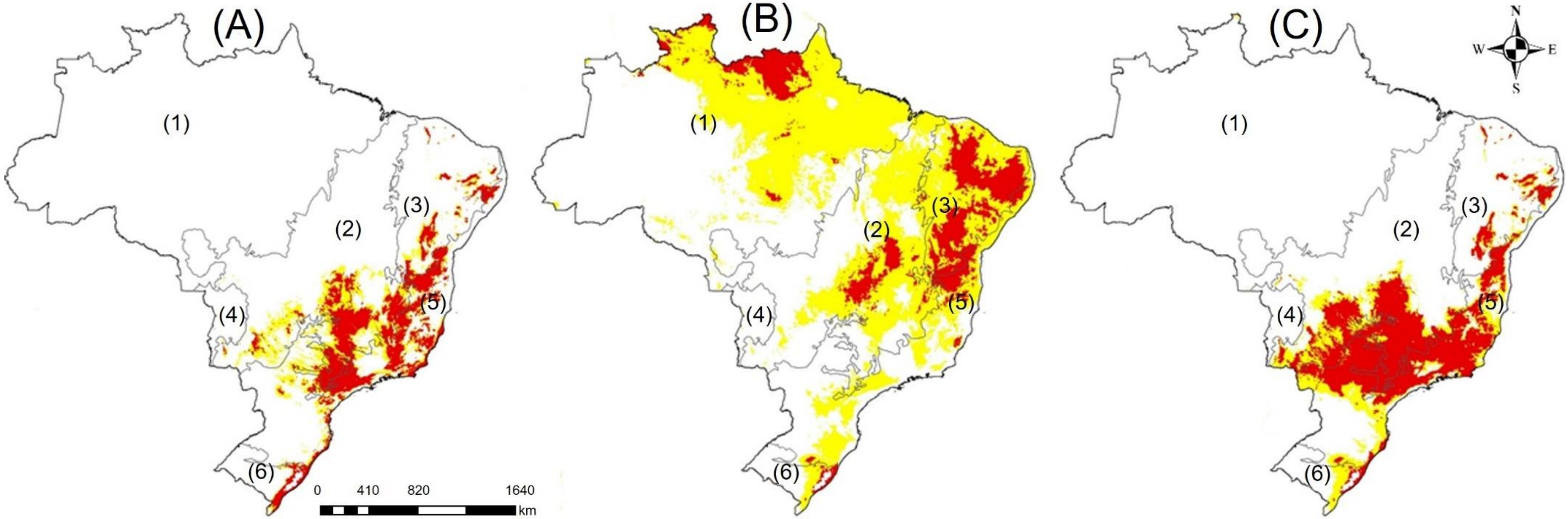
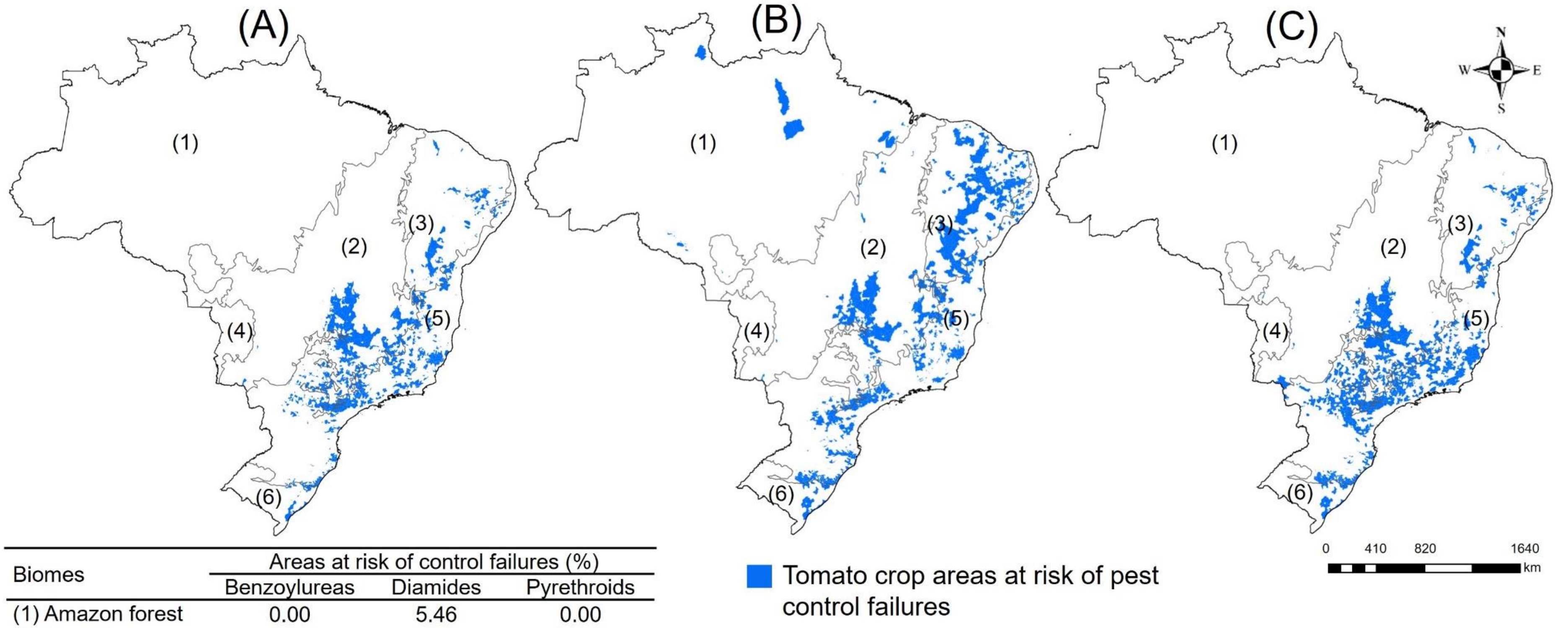


Figure 3. Risks of *Phthorimaea absoluta* control failures by insecticides as a function of the variables of each model. (A) benzoylureas, (B) diamides and pyrethroids. Bio 4 = temperature seasonality (°C), Bio 7 = temperature annual range (°C), Bio 11 = mean temperature of coldest quarter (°C), Bio 12 = annual precipitation (mm), Bio 18 = precipitation of warmest quarter (mm), Bio 19 = precipitation of coldest quarter (mm) and Bio 20 = Elevation of the location (m).



Brazil area	Benzoylureas	Diamides	Pyrethroids
High risk (%)	10.20	11.73	13.94
Medium risk (%)	5.42	32.38	4.45
Low risk (%)	84.38	55.89	81.61

Figure 4. Risks of failures in the control of Phthorimaea absoluta by insecticides from the groups of (A) benzoylureas, (B) diamides, (C) pyrethroids in Brazilian territory.



Biomes	Areas at risk of control failures (%)		
	Benzoylureas	Diamides	Pyrethroids
(1) Amazon forest	0.00	5.46	0.00
(2) Cerrado	11.87	12.33	14.94
(3) Caatinga	9.01	17.89	8.83
(4) Tropical wetlans	0.00	0.00	0.00
(5) Atlantic forest	10.87	10.29	16.21
(6) Lowland plains	0.52	1.10	1.10
Total	32.27	47.07	41.09

Figure 5. Risks of failures in the control of *Phthorimaea absoluta* by insecticides from the groups of (A) benzoylureas, (B) diamides, (C) pyrethroids in areas with crops in Brazilian territory.

6. Supplementary Material

Table 1S. Code, name, unit and percentage contribution of environmental variables for the initial models of spatial distribution of *Phthorimaea absoluta* control failures by insecticides from the benzoylureas, diamides and pyrethroids groups.

Variables		Contribution (%)		
Code	Name	Benzoylureas	Diamides	Pyrethroids
Bio 1	Annual mean temperature (°C)	6.5	7.8	7.8
Bio 2	Mean diurnal range (mean of monthly (max temp - min temp)) (°C)	1.9	2.2	1.1
Bio 3	Isothermality (100 x Bio2/Bio7) (%)	19.8	17.6	20.4
Bio 4	Temperature seasonality (standard deviation ×100) (°C)	12.7	37.3	1.9
Bio 5	Max temperature of warmest month (°C)	0.8	0.2	1.5
Bio 6	Min temperature of coldest month (°C)	0.5	0.2	0.3
Bio 7	Temperature annual range (Bio5-Bio6) (°C)	2.9	4.3	1.9
Bio 8	Mean temperature of wettest quarter (°C)	0.2	0.0	0.1
Bio 9	Mean temperature of driest quarter (°C)	0.1	0.1	0.0
Bio 10	Mean temperature of warmest quarter (°C)	0.3	0.0	0.0
Bio 11	Mean temperature of coldest quarter (°C)	13.0	4.7	11.4
Bio 12	Annual precipitation (mm)	18.6	1.0	37.8
Bio 13	Precipitation of wettest month (mm)	0.0	0.5	0.0
Bio 14	Precipitation of driest month (mm)	6.1	4.8	4.7
Bio 15	Precipitation seasonality (coefficient of variation) (%)	0.4	1.0	0.8
Bio 16	Precipitation of wettest quarter (mm)	3.3	5.3	0.1
Bio 17	Precipitation of driest quarter (mm)	1.0	0.0	1.5
Bio 18	Precipitation of warmest quarter (mm)	1.4	2.0	0.9
Bio 19	Precipitation of coldest quarter (mm)	3.4	0.1	2.4
Bio 20	Elevation (m)	7.2	10.9	5.4

Table 2S. Pearson correlations between environmental variables (Bios) of the initial spatial distribution model in Brazil of the risks of failures in the control of *Phthorimaea absoluta* by insecticides from the benzoylureas, diamides and pyrethroids groups.

BIOS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
										Benzoylureas										
1		0.25	0.75	-0.82	0.94	0.93	-0.39	0.86	0.94	0.96	0.99	-0.50	-0.06	-0.75	0.69	-0.08	-0.75	-0.60	-0.56	-0.63
2	0.17		0.42	-0.32	0.41	-0.06	0.64	0.29	0.11	0.18	0.27	-0.03	0.20	-0.40	0.44	0.21	-0.40	0.06	-0.51	0.17
3	0.76	0.32		-0.88	0.63	0.72	-0.43	0.64	0.69	0.58	0.80	-0.60	-0.05	-0.82	0.80	-0.10	-0.82	-0.53	-0.65	-0.07
4	-0.81	-0.20	-0.88		-0.71	-0.79	0.45	-0.65	-0.77	-0.64	-0.89	0.42	-0.09	0.85	-0.81	-0.08	0.86	0.53	0.69	0.13
5	0.94	0.38	0.65	-0.70		0.82	-0.12	0.79	0.89	0.95	0.92	-0.44	-0.11	-0.62	0.58	-0.11	-0.62	-0.61	-0.48	-0.66
6	0.92	-0.17	0.72	-0.79	0.79		-0.67	0.75	0.94	0.89	0.93	-0.60	-0.21	-0.65	0.58	-0.24	-0.65	-0.74	-0.40	-0.63
7	-0.40	0.73	-0.41	0.45	-0.11	-0.69		-0.27	-0.47	-0.31	-0.42	0.47	0.23	0.32	-0.24	0.27	0.32	0.49	0.07	0.23
8	0.87	0.22	0.62	-0.62	0.81	0.74	-0.25		0.69	0.83	0.82	-0.45	-0.02	-0.71	0.62	-0.03	-0.70	-0.36	-0.62	-0.56
9	0.96	0.02	0.73	-0.80	0.88	0.95	-0.51	0.74		0.92	0.94	-0.50	-0.14	-0.63	0.58	-0.16	-0.63	-0.71	-0.39	-0.63
10	0.96	0.11	0.60	-0.64	0.94	0.89	-0.33	0.86	0.92		0.92	-0.47	-0.14	-0.58	0.53	-0.15	-0.58	-0.60	-0.40	-0.80
11	0.99	0.17	0.81	-0.89	0.92	0.93	-0.43	0.83	0.96	0.92		-0.49	-0.03	-0.79	0.73	-0.04	-0.79	-0.63	-0.60	-0.53
12	-0.51	-0.02	-0.61	0.43	-0.47	-0.60	0.42	-0.46	-0.52	-0.49	-0.50		0.72	0.48	-0.36	0.77	0.47	0.73	0.36	0.30
13	-0.10	0.17	-0.10	-0.03	-0.15	-0.25	0.23	-0.07	-0.17	-0.17	-0.08	0.75		-0.18	0.33	0.99	-0.18	0.58	-0.19	0.29
14	-0.73	-0.38	-0.80	0.82	-0.62	-0.60	0.24	-0.68	-0.63	-0.57	-0.76	0.47	-0.14		-0.91	-0.15	1.00	0.32	0.87	0.10
15	0.67	0.39	0.77	-0.77	0.58	0.54	-0.18	0.59	0.58	0.52	0.70	-0.34	0.31	-0.90		0.28	-0.92	-0.28	-0.80	-0.03
16	-0.13	0.18	-0.15	-0.01	-0.16	-0.28	0.27	-0.09	-0.20	-0.19	-0.10	0.80	0.98	-0.11	0.26		-0.16	0.61	-0.18	0.28
17	-0.73	-0.37	-0.80	0.83	-0.62	-0.60	0.24	-0.67	-0.63	-0.56	-0.76	0.46	-0.15	1.00	-0.90	-0.12		0.32	0.87	0.10
18	-0.62	0.11	-0.58	0.58	-0.62	-0.76	0.51	-0.38	-0.72	-0.61	-0.65	0.74	0.58	0.32	-0.29	0.62	0.32		0.11	0.42
19	-0.44	-0.55	-0.52	0.55	-0.42	-0.23	-0.12	-0.51	-0.28	-0.30	-0.46	0.32	-0.12	0.80	-0.71	-0.11	0.80	0.05		-0.04
20	-0.68	0.21	-0.17	0.19	-0.66	-0.68	0.32	-0.64	-0.66	-0.82	-0.59	0.35	0.29	0.12	-0.07	0.30	0.11	0.45	-0.11	
										Diamides										

BIOS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
2	0.13																		
3	0.74	0.31																	
4	-0.83	-0.18	-0.86																
5	0.93	0.35	0.61	-0.70															
6	0.93	-0.19	0.71	-0.80	0.79														
7	-0.43	0.72	-0.43	0.47	-0.11	-0.70													
8	0.86	0.20	0.65	-0.66	0.78	0.74	-0.30												
9	0.94	0.00	0.69	-0.79	0.88	0.94	-0.50	0.69											
10	0.96	0.07	0.58	-0.65	0.94	0.89	-0.35	0.82	0.92										
11	0.99	0.14	0.79	-0.90	0.91	0.93	-0.45	0.82	0.94	0.92									
12	-0.41	-0.01	-0.57	0.34	-0.33	-0.48	0.39	-0.40	-0.38	-0.37	-0.39								
13	0.02	0.22	0.01	-0.15	-0.01	-0.13	0.19	0.02	-0.04	-0.06	0.05	0.69							
14	-0.68	-0.39	-0.80	0.80	-0.58	-0.56	0.23	-0.66	-0.56	-0.51	-0.72	0.47	-0.21						
15	0.64	0.42	0.79	-0.75	0.55	0.51	-0.18	0.58	0.53	0.48	0.67	-0.38	0.35	-0.91					
16	0.00	0.23	-0.05	-0.15	-0.01	-0.16	0.24	0.00	-0.06	-0.08	0.04	0.75	0.98	-0.19	0.30				
17	-0.69	-0.39	-0.79	0.80	-0.58	-0.56	0.23	-0.66	-0.56	-0.51	-0.72	0.47	-0.22	1.00	-0.92	-0.19			
18	-0.63	0.13	-0.54	0.55	-0.63	-0.76	0.49	-0.39	-0.72	-0.63	-0.65	0.64	0.48	0.31	-0.28	0.51	0.31		
19	-0.29	-0.43	-0.44	0.38	-0.23	-0.13	-0.07	-0.39	-0.12	-0.16	-0.29	0.38	-0.08	0.66	-0.62	-0.06	0.67	-0.02	
20	-0.66	0.26	-0.11	0.21	-0.66	-0.67	0.32	-0.57	-0.66	-0.81	-0.57	0.19	0.21	0.04	0.01	0.21	0.04	0.47	-0.20

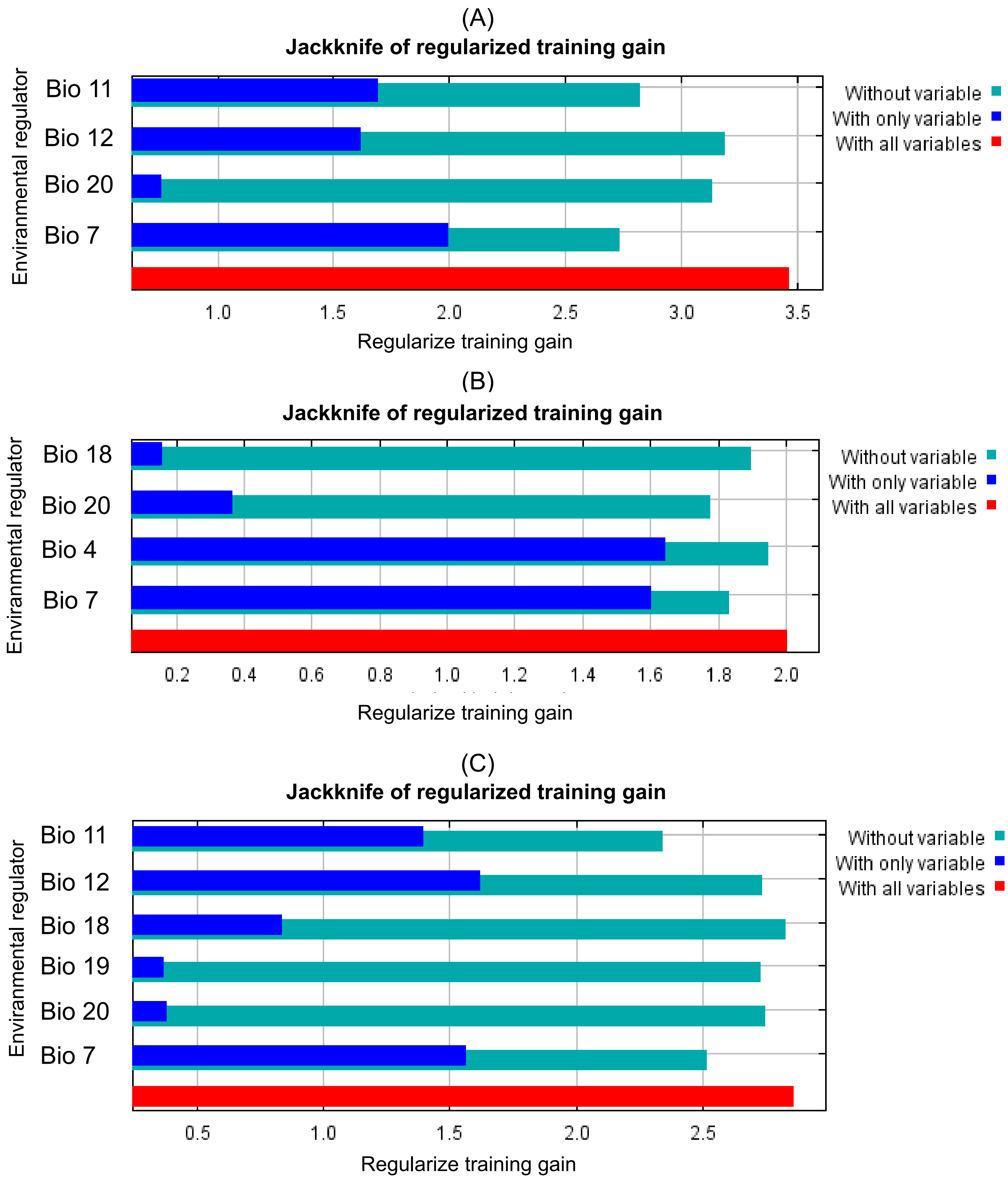


Figure 1S. Relative importance of environmental variables in the final model of geographic distribution in Brazil of *Phthorimaea absoluta* control failures by (A) benzoylureas, (B) diamides, (C) pyrethroids using maximum entropy machine learning algorithm (MaxEnt).

GENERAL CONCLUSION

The results presented in this study allowed us to identify and evaluate temporal and spatial trends in control failures for different chemical groups. Insecticides such as avermectins, spinosyns, and isoxazolines showed consistent effectiveness, while diamides, organophosphates, pyrethroids, and oxadiazines showed loss of effectiveness over time. Benzolureas and nereistoxin analogues have recently returned to good control levels, possibly due to decreased use and reversal of resistance.

The machine learning models (MaxEnt) presented here enable a spatial assessment of the risk of control failures in Brazil, associated with environmental variables. The results showed that regions of the Cerrado, Caatinga, and Atlantic Forest biomes presented a high risk of control failures for insecticides from the benzoylureas, diamides, and pyrethroids groups. Among the environmental factors most associated with these failures are temperature seasonality and annual precipitation. The risks of pest control failures with insecticides from the benzoylureas and pyrethroids groups were higher in tomato crops located in the Cerrado and Atlantic Forest biomes, and annual precipitation was the critical variable associated with these failures. The risks of control failures with diamides were higher in crops located in the Caatinga, Cerrado, and Atlantic Forest biomes, and temperature seasonality was the critical variable associated with these failures.

The information generated in this work will be very useful in direct practical implications for integrated pest management. By identifying regions at higher risk of control failures and the environmental factors that influence them, this work offers a valuable tool for the preventive management of control failures, enabling more informed decisions about the rational use of insecticides in different producing regions.

Therefore, we conclude that the use of artificial intelligence tools, both for literature review and spatial modeling, is promising and applicable on a global scale. This multidisciplinary approach allowed us to identify critical trends in *P. absoluta* control failures and propose targeted solutions. The results presented here are expected to contribute to strengthening insecticide resistance management programs and to more efficient and sustainable tomato production in different regions of the world.