University of São Paulo
"Luiz de Queiroz" College of Agriculture

Agrometeorological modeling of citrus huanglongbing and climatic risk of its occurrence in Brazil and in the United States of America

Silvane Isabel Brand

Thesis presented to obtain the degree of Doctor in Science. Area: Agricultural Systems Engineering

Piracicaba
2021

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Bachelor in Agronomy

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

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Dados Internacionais de Catalogação na Publicação
DIVISÃO DE BIBLIOTECA – DIBD/ESALQ/USP

Brand, Silvane Isabel

Agrometeorological modeling of citrus huanglongbing and climatic risk of its occurrence in Brazil and in the United States of America / Silvane Isabel Brand. - - versão revisada de acordo com a resolução CoPGr 6018 de 2011 - - Piracicaba, 2021.

204 p.

Tese (Doutorado) - - USP / Escola Superior de Agricultura "Luiz de Queiroz".

1. HLB 2. Psilídeo 3. Variáveis meteorológicas 4. Modelos de doenças I. Título

DEDICATION

To my mother Romana and my father Guido.

ACKNOWLEDGMENTS

To God for the gift of life and for all the moments of joy and overcoming provided over these years.

To my mother Romana and my father Guido who, even though did not have the opportunity to study, gave me all the opportunities to invest in my graduation. Thank you so much for all the care, support, and encouragement throughout my life.

To my sister Simone, who always helped me during my academic life. She is my professional colleague. Thank you for everything.

To Professor Paulo Cesar Sentelhas for the advising me during my doctorate, and also for contributing to my personal and professional growth and friendship.

To 'Luiz de Queiroz' College of Agriculture (ESALQ), University of São Paulo, and to the Graduate Program in Agricultural Systems Engineering for the opportunity to pursue a doctorate.

The Coordination for the Improvement of Higher Education Personnel – CAPES, for granting a scholarship during part of the doctorate (25 months).

To São Paulo Research Foundation – FAPESP, for the PhD scholarship (Process 2017/23497-9, 17 months) and internship abroad scholarship (Process N° 2019/12174-0, 6 months) at Iowa State University.

To the defense board members, Leandro Maria Gimenez, José Belasque Junior, and Francisco Ferraz Laranjeiras Barbosa for their contributions to the improvement of this study.

To Professor Mark Gleason for his teachings, guidance, and friendship during the exchange period at Iowa State University.

To Professor José Belasque Junior and CITROSUCO company for making HLB data in the state of São Paulo, Brazil, available and for helping me during the development of the project. To Dr. Lauren M. Diepenbrock for allowing me to use HLB data from farms in Florida, USA, in this project.

To Professor Sidinei Zwick Radons for his guidance during the entire undergraduate course and for his co-supervision during my master's degree. Also, for introducing me to the area of agrometeorology.

To Professor Arno Bernardo Heldwein for his guidance, teaching and the opportunity to pursue my Master´s degree under his supervision.

To my colleagues of ESALQ's Agrometeorology laboratory for their friendship and for the good moments we spent together.

Finally, I would like to thank everyone who contributed directly or indirectly to my thesis.

“Your work is going to fill a large part of your life, and the only way to be truly satisfied is to do what you believe is great work. And the only way to do great work is to love what you do. If you haven´t found it yet, keep looking. Don´t settle. As with all matters of the heart, you´ll know when you find it.”

Steve Jobs

SUMMARY

RESUMO

Modelagem agrometeorológica do huanglongbing dos citros e risco climático para sua ocorrência no Brasil e nos Estados Unidos

O huanglongbing (HLB) é a principal doença atual dos citros e vem promovendo redução expressiva na produtividade dos pomares. O HLB é um patossistema que tem o psilídeo como agente transmissor da bactéria, *Candidatus* Liberibacter asiaticus. Esse vetor é atraído até as plantras de citros quando há disponibilidade de brotações novas e sob condições climáticas adequadas para seu desenvolvimento. Sendo assim, a determinação das melhores condições para o ataque desse inseto e transmissão do HLB é fundamental para que se possa fazer o controle racional dessa doença. Diante disso, os objetivos deste estudo foram: i) desenvolver, calibrar e validar um modelo agrometeorológico para prever a ocorrência do psilídeo com base em dados de captura do psilídeo em pomares dos estados de São Paulo, Brasil, e Flórida, Estados Unidos; ii) elaborar mapas de risco de ocorrência do psilídeo para os estados de São Paulo, assim como para os estados americanos da Califórnia, Flórida e Texas; iii) desenvolver, calibrar e validar um modelo agrometeorológico que estima a proporção de plantas com sintomas de HLB com base na ocorrência do vetor e de condições meteorológicas que favorecem o desenvolvimento da bactéria e confeccionar mapas de risco para isso no estado de São Paulo; e iv) avaliar o efeito do fenômeno El Niño Oscilação Sul (ENOS) no risco de ocorrência do psilídeo e do HLB para os estados de São Paulo e da Flórida. Para modelar a ocorrência do psilídeo foram utilizados dados de oito fazendas do Estado de São Paulo, sendo cinco utilizadas para calibrar e três para validar o modelo proposto. Esse modelo também foi validado com dados de captura de psilideos em 53 fazendas situadas no estado da Flórida. Os dados meteorológicos (temperatura máxima, mínima e média, umidade relativa, velocidade do vento e chuva) utilizados nos modelos foram obtidos das seguintes bases: base de dados em grade de Xavier e de estações instaladas nas proximidades das fazendas brasileiras; base de dados em grade dos sistemas PRISM e NASA/POWER para as fazendas americanas. Uma vez com o modelo de estimação da captura de psilídeos calibrado e validado, este foi empregado na espacialização do risco de infestação desse vetor nos pomares dos principais estados produtores do Brasil e dos Estados Unidos. O modelo de estimação da proporção de plantas infectadas pelo HLB se baseou no número de plantas erradicadas nas oito fazendas do estado de São Paulo, sendo os dados de cinco delas empregados na calibração e de três delas na validação. Esse modelo teve como variáveis independentes o número de psilídeos capturados, resultante do modelo aqui proposto, e a temperatura do ar que favorece o desenvolvimento da bactéria causadora da doença. Após a calibração e a validação, esse modelo foi empregado na espacialização do risco de ocorrência do HLB para o estado de São Paulo. Por fim, avaliou-se o efeito das diferentes fases do ENOS, com fraca, moderada e forte intensidades, no risco de ocorrência do psilídeo e do HLB. A ocorrência do psilídeo se baseou na estimativa da brotação dos citros, a qual ocorre sempre quando há déficit hídrico de 5 mm ou mais, seguido de precipitação de 5 mm e temperatura entre 16 e 28 °C. Esse modelo apresentou um acerto superior a 90% para os estados de São Paulo e da Flórida. O risco de ocorrência do psilídeo se mostrou superior no centro, leste e parte do norte no estado de São Paulo, enquanto nos estados americanos há maior risco no sul. O risco é maior no estado da Flórida, seguido pelos estados de São Paulo, do Texas e da Califórnia. Ao longo dos meses o risco é maior na primavera no Estado de São Paulo, começando a aumentar em setembro e perdurando até dezembro. Nos Estados Unidos, o risco é maior no verão. O modelo que estima a ocorrência do HLB se baseou na população de psilídeo capturada 18 meses antes da estimação e na temperatura do mês da erradicação, possuindo acerto variável, porém considerado bom (média de cerca de 70% calibração e validação 66%). Quanto ao risco de ocorrência do HLB se mostrou maior no sul e centro do estado de São Paulo, porém variando ao longo do ano sendo maior nas regiões centro, leste e sul do estado, sendo maior no outono e em parte do inverno. O risco de ocorrência do psilídeo associado às diferentes fases do ENOS é maior nos anos de La Niña moderada no estado de São Paulo e La Niña forte no estado da Florida, sendo que no primeiro o maior risco ocorre na primavera e no verão e no segundo no verão. Quando não se considera a intensidade da fase do ENOS, o maior risco em São Paulo ocorre nos anos Neutros, enquanto na Florida nos anos de La Niña. Já quando se avalia o risco associado à ocorrência do HLB este é maior em anos Neutros do ENOS para o estado de São Paulo, sendo os meses do outono e do inverno os de maiores riscos.

Palavras-chave: HLB, Psilídeo, Variáveis meteorológicas, Modelos de doenças

ABSTRACT

Agrometeorological modeling of citrus huanglongbing and climatic risk of its occurrence in Brazil and the United States of America

Huanglongbing (HLB) is the main current citrus disease and has been promoting a significant reduction in orchards productivities. HLB is a pathosystem that has the psyllid as a transmitting agent for the bacterium, *Candidatus* Liberibacter asiaticus. This vector is attracted to citrus plants when new sprouts are available and under suitable climatic conditions for their development. Therefore, the determination of the best conditions for the attack of this insect and transmission of HLB is fundamental for the rational control of this disease. Therefore, the objectives of this study were: i) to develop, calibrate and validate an agrometeorological model to predict the occurrence of the psyllid based on data from captures of the insect in citrus orchards in the states of São Paulo, Brazil, and Florida, United States; ii) to develop risk maps for the occurrence of psyllids for the states of São Paulo, as well as for the American states of California, Florida and Texas; iii) to develop, calibrate and validate an agrometeorological model to estimate the proportion of plants with symptoms of HLB based on the occurrence of the vector and meteorological conditions that favor the development of the bacterium and make risk maps for that in the state of São Paulo; and iv) to evaluate the effect of the El Niño Southern Oscillation (ENSO) phases on the risk of occurrence of psyllid and HLB for the states of São Paulo and Florida. To model the occurrence of the psyllid, data from eight farms in the State of São Paulo were used, being five for model calibration and three for model validation. This model was also validated with data from psyllid captures from 53 farms located in the state of Florida. The meteorological data (maximum, minimum and average temperature, relative humidity, wind speed and rain) used in the models were obtained from the following databases: Xavier grid database and stations installed close to the Brazilian farms; grid database of PRISM and NASA/POWER systems for the American states. Once the psyllid capture estimation model was calibrated and validated, it was used to spatialize the risk of infestation of this vector in the orchards of the main producing states in Brazil and the United States. The estimation model of the proportion of plants infected by HLB was based on the number of plants eradicated in the eight farms in the state of São Paulo, with data from five of them used in calibration and three of them in validation. This model had as independent variables the number of captured psyllids, resulting from the model proposed here, and the air temperature that favors the development of the disease-causing bacterium. After calibration and validation, this model was used to spatialize the risk of occurrence of HLB for the state of São Paulo. Finally, the effect of the different phases of ENSO, with low, moderate, and high intensities, on the risk of occurrence of psyllid and HLB was evaluated. The occurrence of the psyllid was based on the estimated of citrus sprouting, which always occurs when there is a water deficit of 5 mm or more, followed by rainfall of 5 mm and temperature between 16 and 28 °C. This model presented 90% correctness for the states of São Paulo and Florida. The risk of occurrence of the psyllid was higher in the center, east and part of the north of the state of São Paulo, while in the American states there is a greater risk in the south. The risk is greatest in the state of Florida, followed by the states of São Paulo, Texas and California. Over the months, the risk is greater in the spring in the State of São Paulo, starting to increase in September and lasting until December. In the United States, the risk is greatest in the summer. The model that estimates the occurrence of HLB was based on the population of psyllid captured 18 months before the estimation and on the temperature of the month of eradication, presenting a good performance (average around 70% calibration and 66% validation). The risk of HLB occurrence was higher in the south and center of the state of São Paulo, but it varied throughout the year being bigger in the central, south and east regions of the state, being higher in autumn and part of winter. The risk of occurrence of the psyllid associated with the different phases of ENOS is greater in the years of moderate La Niña in the state of São Paulo and strong La Niña in the state of Florida, with the former having the greatest risk in spring and summer and for the latter in the summer. When the intensity of the ENOS phase is not considered, the greatest risk in São Paulo occurs in the Neutral years, while in Florida in the La Niña years. When assessing the risk associated with the occurrence of HLB, it is higher in ENSO Neutral years for the state of São Paulo, with the autumn and winter months having the greatest risk.

Keywords: HLB, Psyllid, Meteorological variables, Disease models

1. INTRODUCTION

The citrus has characteristics that make possible to cultivate it in different climatic conditions, subtropical to equatorial climates, as well as from more humid to drier regions (REUTHER, 1973). Although its cultivation is quite wide, most of it is concentrated in the tropics and subtropics, where water availability and thermal conditions are suitable for producing high yields and fruits of superior quality (SENTELHAS, 2005). The thermal characteristics for the development of citrus are air temperatures from 12 °C to 31 °C. Beyond this limit, the citrus plants has their yields decreased, with its growth being stopped above 37 °C (REUTHER, 1973). Even considering that citrus plants can adapt to different environments, such as drier regions, this leads to changes yield levels, phenology, fruit quality, and, also, in crop evapotranspiration, making irrigation required for its cultivation, like in some areas of Spain and Brazil (SENTELHAS, 2005). The water requirement for obtaining high citrus yield is between 900 to 1,200 mm year^{-1}, which varies according to the local climate conditions (DOORENBOS; KASSAM, 1994).

In general, in tropical climates, the citrus plants vegetate all year long, whereas in the subtropical climates the plants present a reduction in the growth caused by water deficiency and/or low temperatures. Under these conditions, the sprouting and regrowth return in the beginning of the rainy season, when temperatures and photoperiod also increase (DAVIES; ALBRIGO, 1994). Usually, after a period of water deficit, the occurrence of rainfalls above 20 mm induces sprouting and flowering, processes also influenced by root growth (RAMOS et al., 2010; SOARES-COLLETTI, 2016), since, even under favorable conditions, sprouting often does not occur when the root growth process is happening. According to Bevington and Castle (1985), there is an inhibition of aerial growth when citrus root growth occurs, which explain why flowering and sprouting in citrus just occur after a period of water deficiency and or low temperatures followed by the return of the rains (DA CRUZ et al., 2007).

Among the challenges to produce citrus around the world, the occurrence of diseases is the most important. Among the diseases that affect citrus orchards in the producing regions of the world, huanglongbing (HLB), also known as greening, has been the major problem. The first reports of huanglongbing was in 1919 in China and in 1937 in Africa (GRAÇA, 1991). In Brazil, the first report of this disease was in 2004, in Araraquara, state of São Paulo (COLETTA-FILHO et al., 2004). One year later, HLB was reported in Florida (HALBERT, 2005), and in 2012 the disease was observed occurring in the orchards of California (KUMAGAI et al., 2013) and Texas (DA GRAÇA et al., 2015). HLB is the main citrus disease worldwide (GRAÇA, 1991; COLETTA-FILHO et al., 2004; BRUCE et al., 2005), causing serious damages to citrus productivity, promoting the eradication of millions of plants and, consequently, reducing the total production around the world. Between 2004 and 2014, more than 40 million plants with HLB symptoms were eradicated in the state of São Paulo and in the west of the state of Minas Gerais (Triângulo Mineiro), Brazil (NEVES et al., 2010), with the disease also occurring in the states of Paraná, in other regions of Minas Gerais (BELASQUE JUNIOR et al., 2009) and Mato Grosso do Sul (MAPA, 2018). In the USA, citrus production and area decreased in the 2016/17 growing season as a result of HLB, especially in Florida, the main American producing state (USDA, 2020).

HLB is a disease caused by bacteria whose species are: *Candidatus* Liberibacter africanus (*Ca*. L. africanus), *Candidatus* Liberibacter asiaticus (*Ca*. L. asiaticus) and *Candidatus* Liberibacter americanus (*Ca*. L. americanus) (BOVÉ, 2006), with the last two already recorded in Brazil (GASPAROTO et al., 2012). *Ca*. L. asiaticus is the specie recordedin the United States (MANJUNATH et al., 2008) and is also the one that currently predominates in Brazil (LOPES et al., 2009). *Ca*. L. africanus is more sensitive to heat, since temperatures ≥ 32 °C and low air humidity are harmful to the establishment of the disease, which is favored by conditions of air humidity above 25% and altitude above 600 m (BOVÉ, 2006). According to Lopes et al. (2009) and Gasparoto et al. (2012), *Ca*. L. asiaticus is more resistant to higher temperatures when compared to *Ca*. L. americanus, both of which are more tolerant to high temperatures when compared to *Ca*. L. africanus. Therefore, *Ca*. L. asiaticus presents growth restrictions when submitted to temperatures above 38 °C, and up to 35 °C there was no drastic reduction of the disease. On the other hand, the *Ca*. L. americanus presents a limited growth at temperatures greater than or equal to 32 °C (LOPES et al., 2009). Gasparoto et al. (2012) found a difference regarding the thermal requirement of the two bacteria mentioned above. According to these authors, *Ca*. L. asiaticus had a higher tolerance to higher temperatures, from 27 °C to 32 °C, while *Ca*. L. americanus had its colonization capacity negatively affected when temperatures were between 27 °C to 32 °C, presenting lower concentration and less efficient for its transmission by the vector.

Regarding the symptoms of HLB, plants infected by the bacterium have yellowish-colored leaves, which, with the progress of the disease, may lead to leaf fall and formation of smaller branches. The symptoms in the fruits are similar to those observed in the leaves, presenting yellowish spots, asymmetrical form and miscarriage of the seeds, as well as premature fall. In addition, infected plants become unproductive in a few years, requiring their eradication, which, in turn, increases production costs (BOVÉ, 2006; BOSCARIOL-CAMARGO et al., 2010).

The transmission of the disease occurs through psyllids: *Diaphorina citri* (GALLO; GALLO, 2002) and *Trioza erytreae* (MCCLEAN; OBERHOLZER, 1965); however, only the first one occurs in Brazil (COSTA LIMA, 1940) and in the United States (TSAI; LIU 2000). The development rate of the vector varies according to the air temperature favorable to the insect, which ranges between 10 to 41°C (LIU; TSAI, 2000; NAVA et al., 2007; MOSCHINI et al., 2010; HALL et al., 2011; TORRES- PACHECO et al., 2013). The development of *D. citri* requires a thermal accumulation, in terms of degrees days, from egg until adult, of about 211 °C day, with a basal temperature of 13.5 ºC (NAVA et al., 2007). The period required to complete the five nymph instars is about 15 days (NAVA et al., 2007) and the largest vector´s population occurs during the wet season (BOVÉ, 2006). In Brazil, the population of the HLB´s vector tends to be greater during spring and summer; however the vector is present throughout the year, requiring constant monitoring by the growers (BASSANEZI et al., 2010). The adults of *D. citri* feed on new and mature tissues, but preferably on the new ones, which makes the availability of new sproutings a decisive factor for vector population growth, once oviposition also occurs in this type of tissue (PARRA et al., 2010). Diniz (2013) found that sproutings from 1 to 2.6 cm are more favorable to oviposition, while adults of *D. citri* feed on larger sproutings, of about 4.3 cm.

Regarding the instars for acquiring the bacterium, fourth and fifth are those most favorable ones. The time the insect needs to be in contact with the infected plant to acquire the pathogen is between 15 and 30 minutes, after which it undergoes a latency period of one to two weeks to become a bacteria transmitting agent. About an hour of feeding is required for inoculating the bacterium in the citrus plants. The average life span of the vector is from 2 to 3 months, a period in which it can transmit the pathogen (NAVA et al., 2007; PARRA et al., 2010). Transovarian transmission of the causative agent of HLB also occurs, but it has a low rate (PELZ-STELINSKI et al., 2010).

Even considering all aspects above, the mere occurrence of the psyllid does not guarantee the occurrence of HLB. According to Lopes et al. (2009), transmission varies according to the bacterium specie, being 55% to 88% for *Ca*. L. asiaticus and 10% to 45% for *Ca*. L. americanus, with 40% of the co-inoculated plants containing the first and 13% the second, respectively, while 19% already contained both species of the pathogen. Regarding the rate of acquisition of the bacterium of HLB, 74% and 52% were found for adults and nymphs, respectively, with transmission in adults at one week of age being 12%, whereas for nymphs of the third instar was 43% (CANALE et al., 2016). According to the same authors, the nymph of the third instar that acquires the pathogen transmits the disease after 11 to 33 days, with an average transmission rate of 6%, varying between 0 and 22%. Regarding the persistence of the bacteria in the psyllid, it was 70% in the first and second weeks, 75 to 80% between the third and fifth weeks and then decreased to 40% in the sixth, seventh and eighth weeks, with the average rate of transmission after the fifth week varying between 2 and 4%, whereas in the subsequent weeks the transmission was null

(CANALE et al., 2016). Folimonova and Achor (2010) evaluated the occurrence of symptoms of HLB and the occurrence of its transmission in citrus plants and found greater transmission in the sprouts that were pre-symptomatic, where a greater number of bacteria were found compared to highly symptomatic sprouts, where no HLB-causing bacteria were found.

In relation to the HLB control/management, the eradication of citrus-infected plants is the most common, since these plants are source of inoculum for new transmissions and also because they become unproductive and economically unfeasible between seven and ten years after the appearance of the first symptoms (BELASQUE JUNIOR et al., 2009). When the infection occurs in young orchards, up to four years old, they become unfeasible five years after the infection (GOTTWALD et al., 2007). However, due to the long incubation period, which varies from 6 to 12 months (BOVÉ, 2006), the eradication of symptomatic plants does not guarantee the elimination of the disease from the area. Canale et al. (2016), evaluating plants inoculated by the bacteria, found the presence of symptoms five months after the infection. It means that infected plants, which do not present symptoms, already have the capacity to serve as a source of inoculum for two to four months after acquiring the disease-causing bacteria (BELASQUE JUNIOR et al., 2009; 2010).

Another strategy for HLB management is the chemical control of the vector. If this strategy is not used, the proportion of infected plants can reach 80% in a very short time (BASSANEZI et al., 2013). However, according to the same authors, if the disease management occurs at the farm level, the proportion of plants with HLB can be around 50%. On the other hand, if the regional management is adopted, which implies to adopt the HLB control outside the farms, the proportion of plants with HLB can be reduced to 6%, while the combination of regional and local HLB management can further reduce the occurrence of this disease to 4%.

In view of the importance of HLB control for guarantee the sustainability of citrus production around the world, it is necessary to know the conditions that favor development and dispersion of the vector and, consequently, of the disease, making possible to identify the areas of greatest risk for the occurrence of HLB, both at the regional and local levels and to establish strategies for a more efficient control of this important disease. Therefore, the hypothesis of the present study is that weather conditions affect citrus plants growth, as well as the development and dispersion of psyllids and HLB and, as a result of that, it is possible to establish the areas of greatest risk for the occurrence of this disease and the most effective strategies for its control.

1.1. Objectives

The general objective of this study was to develop a disease simulation model, including two sub-models for psyllid population estimation and HLB occurrence, based on citrus growth and weather conditions, to determine the areas of higher risk for this disease, at regional and local (farm) levels, an aid for a more effective control/management of HLB.

1.1.1. Specific objectives

The specific objectives of this study were:

a) to establish the relationship between the population dynamics of the psyllid and the weather conditions;
b) to determine the temporal and spatial variation of the psyllid population in citrus producing areas;
c) to develop a model to predict sprouting in citrus, as the basis for favorable conditions for the oviposition and initial vector development in citrus plants;
d) to combine the model of psyllid population dynamics with the growth of citrus in order to determine the occurrence of the psyllid and HLB;
e) to determine the zones with higher risks of psyllid and HLB occurrence in the citrus producing regions of Brazil and United States, based on the proposed models;
f) to determine the zones with higher risks of HLB occurrence in the citrus producing regions of Brazil, based on the proposed models;
g) to validate the risk zones for psyllid and HLB in the citrus producing regions of Brazil and United States, based on field data, to prove the suitability of the maps produced; and
h) to assess the effect of different phases of El Niño Southern Oscillation (ENSO) on the psyllid population dynamics and HLB occurrence in the citrus producing regions of Brazil and United States.

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2. AGROMETEOROLOGICAL MODELING OF HUANGLONGBING (HLB) TRANSMITTING PSYLLID POPULATION DYNAMICS IN CITRUS ORCHARDS

ABSTRACT

Citrus orchards can be cultivated under different climate conditions around the world. The phenology and productivity of citrus orchards dependent mainly on the interaction between the variety used and the climate conditions. However, other aspects can affect this crop, like pests and diseases. Among the diseases, the most important in the present for the majority of the producing regions around the world is huanglongbing (HLB), which is caused by a bacterium that colonizes the phloem of the plants and is transmitted by a vector, the psyllid. The psyllid is attracked to citrus plants when there are availability of new tissues. It occurs under favorable weather conditions for crop sprouting, which allows the vector to transmit the bacterium to the citrus trees, causing losses of production and also plants´ eradication. Climatic conditions directly interfere in the occurrence of crop sprouting and, consequently, in the occurrence of the vector of HLB. Therefore, it is important to understand how climatic conditions affect the psyllids population dynamics and how it can affetc HLB incidence. In view of that, the objective of this study were: i) to develop an agrometeorological model for estimating the occurrence of citrus sprout coupled with climatic factors that affect the psyllid population dynamic seeking to assist in the rational HLB vector control, ii) calibrate and validate the proposed model using field data from eight farms in the State of São Paulo, Brazil, and 53 farms in Florida, USA. Psyllid capture data were obtained weekly per farms´ block for both states. The meteorological data used in this study were obtained from weather stations installed in the farms or very close to them, and then submitted to a consistency analysis. The model that aims to estimate the occurrence of psyllids in citrus orchards was based on climatic factors that affect its occurrence and those that have influence on citrus trees growth and development. Thus, a matrix of correlations was created between the number of psyllids per block (dependent variable) and all the other independent variables associated to weather conditions. The independent variables that showed the best correlation with number of psyllids per block were used to develop the estimation model. First, the model was adjusted (calibrated) using data from five farms in the state of São Paulo, and then validated with observed data from three farms in the state of São Paulo and 53 farms in the state of Florida. The model was evaluated using a contingency table in which five levels of control, 0, 1, 2, 3 and 4 psyllids per block, were considered. The sensitivity of the models to changes in their input parameters was also assessed by decreasing and increasing temperature and rainfall data in relation to their original values. The model with the best performance was the one that considered the estimated citrus´ sprout, influenced by water deficit (WD) and rainfall (R), combined with air temperature (T) conditions that favor psyllids development. The reference values considered in this model were: WD $\geq$ 5 mm, followed by R $\geq$ 5 mm and T between 16 and 28 °C. This model presented more than 90% of correctness during the validation and was sensitive to changes in its input parameters for both states.

Keywords: *Diaphorina citri*, *Candidatus* Liberibacter asiaticus, Meteorological variables, Citrus diseases, Simulation models.

2.1. Introduction

The citrus, mainly orange, are grown in a wide area around the world due to its adaptability to a large range of temperature (REUTHER, 1973). However, the main world producers are Brazil and the United States, which together represent the largest part of the orange produced in the world (FAOSTAT, 2021). In Brazil, the main citrus producing region is in the Southeast region, with the state of São Paulo being the largest producer, responsible for 75% of the national production in 2020 growing season (IBGE, 2021). In the United States, the main producing state is Florida, which accounts for about 52% of total national production (USDA, 2020).

Among the factors that affect orange production in Brazil and United States, plant diseases are the most important, with Huanglongbing (HLB) appearing as the most harmful. HLB is a bacterial disease, caused by different species of bacteria, *Candidatus* Liberibacter asiaticus and *Candidatus* Liberibacter americanus (LOPES et al., 2009; GASPAROTO et al., 2012; DO CARMO TEIXEIRA et al., 2005). The first is the one with the highest occurrence in Brazil (LOPES et al., 2009) and in the United States (MANJUNATH et al., 2008). These bacteria colonize the plant's phloem (GARNIER; DANEL; BOVÉ, 1984), promoting its obstruction due to sucrose accumulation (KIM et al., 2009).

The bacterium that causes the disease needs a vector for its transmission. Both in Brazil and in the United States, the bacteria transmitting agent is the psyllid *Diaphorina citri* (COSTA LIMA, 1940; TSAI; LIU 2000). This insect is small in size and has a preference for feeding and ovipositiong in sprouts (PARRA et al., 2010). In addition, the insect grows over a wide range of temperature (LIU; TSAI, 2000; NAVA et al., 2007; MOSCHINI et al., 2010; HALL et al., 2011; TORRES-PACHECO et al., 2013), which makes possible its occurrence wherever the citrus plants are cultivated (GRAÇA, 1991; COLETTA-FILHO et al., 2004; BRUCE et al., 2005). HLB promotes, over the years, a reduction in fruits number and size, causing a gradual decrease in production, leading to the necessity of plants eradication (BASSANEZI et al., 2011; NEVES et al., 2010).

The most attractive phase of citrus growth for the vector is when the plants start to sprout, since the adults prefer to oviposit on the young tissues, where the nymphs are able to feed (PARRA et al., 2010). Based on that, special attention should be given for this stage of citrus development when the focus is the correct control of HLB vector in order to reduce the negative impacts of this disease (BELASQUE JUNIOR et al., 2009; GOTTWALD et al 2007).

As the HLB-transmitting agent is an insect-vector and it moves from one location to another, it can infect a large number of plants in the farm. In addition to that, when moving from one place to another, there is also the possibility of contamination between farms in the same region (BASSANEZI et al., 2010; BERGAMIN FILHO et al., 2016), which requires not only the vector monitoring and controlling in the farm, but also on the neighboring farms.

Considering the great importance of HLB vector control for the sustainability of citrus production around the world, this has as hypothesis that psyllid population dynamic can be estimated based on the factor that favor its occurrence in citrus orchards in the meteorological data. Therefore, the aim of this study was to develop a agrometeorological model for estimating psyllid population dynamic, based on the occurrence of citrus trees´ estimated sprouts combined with weather conditions that favor HLB vector development, calibrate the model with data from five farms in the state of São Paulo, Brazil, and validate it with data from three farms in the state of São Paulo and other 53 farms in the state of Florida, USA.

2.2. Material and Methods

2.2.1. Sampling of psyllid population

Samplings of psyllids population were obtained in orange orchards in eight citrus farms in the state of São Paulo, Brazil (Figure 1A), with georeferenced yellow adhesive traps fixed in citrus plants mostly located in the edge of the farms and collected during the period from 2015 to 2017. Although most of the data is from the edge of the farms, in the state of São Paulo, Brazil, the few captures from the interior of the blocks are comparable to those on the edge. For the state of Florida, USA, the psyllids population data were from 53 farms and obtained for the period between 2011 and 2019 (Figure 1B). The psyllids capture in Florida were done with tap sampling in 10 plants in the edge and 10 inside the farms every 21 days. Although the capture methods were different in the two countries, they present similarities which make the results comparable (Hall et al., 2007). All these data were submitted to a consistency analysis, and they were expressed in terms of number of psyllids per block (a block represents the production unit in the farms). The consistency analysis aims to identify typing errors and outliers. In the state of São Paulo, the traps were changed almost every seven days, whereas in the state of Florida it was done in a fixed interval of 21 days. For making all these data with the same magnitude, the weekly captures in the farms of São Paulo were summed for an interval of 21 days, and subsequent evaluation of the percentage every 7 days within the 21-day interval, for later evaluation of the model in Florida also every 7 days.

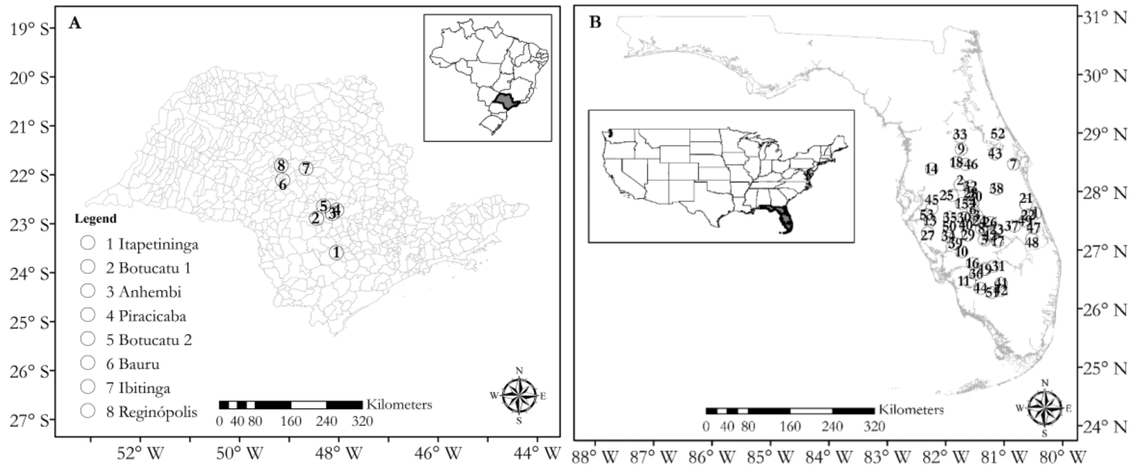

Figure 1. Location of the eight farms in the state of São Paulo, Brazil (A) and 53 farms in the state of Florida, United States (B), from where the psyllid populations were sampled.

2.2.2. Weather data

The weather data used for modeling the psyllid captures in orange orchards in the state of São Paulo, Brazil, were those that mostly affect the psyllid development and survival: maximum, minimum and average air temperature; relative humidity; rainfall; and wind speed. These data were obtained from the grid database of Xavier et al. (2016), for the period from 2015 to 2017. They were submitted to a consistency analysis for verifying whether they corresponded to the observations done by ground stations, like the study conducted by Duarte and Sentelhas (2020). To fill the gaps of rainfall data for the year 2017, the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station Data, 2018) grid database was used. To complete the missing maximum, minimum, and average air temperature, relative humidity and wind speed data, the database of the Meteorological Database for Teaching and Research (BDMEP) of National Institute of Meteorology (INMET) was employed, considering the closest station to the farms. The weather data used in this study for the state of Florida were obtained for each farm from PRISM Climate Group website, comprising the period from 2011 to 2019. The wind speed data were obtained from the NASA/POWER system. All these data were submitted to a consistency analysis, using the same procedures employed in the state of São Paulo.

Considering the climate classification of the assessed locations, the farm located in Ibitinga, SP, is the only one that has a Cwa climate, according to the Köppen climate system, which represents a subtropical climate with dry winter. The other farms have the Cfa climatic type, which is a subtropical climate with humid summer and without a well-defined dry season (ALVARES et al., 2013). In Florida, the climates of the assessed farms are Cfa, Am and Aw. The two A type climates differ in terms of intensity of dry season, but both has dry winter (ACKERMAN, 1941;

HELA, 1952; PEEL et al., 2007). Regarding the soil types in the farms in the state of São Paulo predominate Oxisols and Ultisols (SANTOS et al., 2013), whereas in the state of Florida Inceptisols, Spodosols and Entisols are the most common ones (ESRI; USDA; NRCS, 2017).

2.2.3. Modeling the psyllid capture in orange orchards

To model the dynamic of psyllid population in orange orchards, the data of captures from the georeferenced traps were used, as well as information of the crop. As the HLB vector presents an increase in its population predominantly when the orange trees are sprouting (PARRA et al., 2010), it was considered as one of the factors that favors the increase of psyllid population. According to Garcia Junior et al. (1997) and Jesus Junior et al. (2008), water deficit is the variable that most reduces the citrus sprouts, while the return of rainfall after that, promotes intense flux of citrus sprouts (DAVIES; ALBRIGO, 1994; RAMOS et al., 2010) (Table 1). To determine the water deficit of the orange orchards in the assessed farms, the climatological water balance was calculated according to the method of Thornthwaite and Mather (1955), in a daily scale. For that, rainfall (R) and potential evapotranspiration (ETP), estimated by Penman-Monteith model (ALLEN et al., 1998), were used as input data. Due to the clay characteristics of the soils of all farms, a soil water holding capacity (SWHC) of 100 mm was used for water balance calculation (PEREIRA et al., 2002). From R, ETP and SWHC, the climatological water balance allows to estimate the actual evapotranspiration (ETA), water deficit (WD = ETP - ETA) and water excess (WE). The weather (Tmax, Tmin, Tavg, R, ETP) and water balance (WD and WS) variables together with the number of psyllid generations, calculated according to the degree-days requirement (Thermal time = 211 °C day and base temperature = 13.5 °C), were used as the environmental drives of citrus sprouting and psyllid capture (REUTHER, 1973; DAVIES; ALBRIGO, 1994; RIBEIRO et al., 2012; LEE et al., 2015).

Considering the aspects that interfere in the HLB vector population dynamic, the weather variables that most affect that and citrus sprouting were evaluated, according to thresholds proposed by Catling (1970), Kriedemann (1971), Davies and Albrigo (1994), Liu and Tsai (2000), Nava et al. (2007), Aurambout et al. (2009), Moschini et al. (2010), Parra et al. (2010), Ramos et al. (2010), Hall et al. (2011), Ribeiro et al. (2012), Torres-Pacheco et al. (2013), Lee et al. (2015) and Soares-Colletti et al. (2016), which are presented in Table 2. These thresholds were correlated to the number of psyllids per block in the farms in the state of São Paulo, in a weekly basis, in order to verify which of these variables are more related to the vector captures. The step-by-step of this procedure is presented in Figure 2. To assess the degree of correlations between weather variables and psyllid capture, Pearson's coefficient at 1 and 5% of significance was used (SNEDECOR; COCHRAN, 1971). Those variables that presented highest significance were combined and considered for modeling psyllid capture.

Table 1. Weather and weather-derived variables with their thresholds to be considered in the psyllid capture modeling.

Weather and weather-derived variables*	**References****
# days with Tmin > 13 °C and Tmax < 35 °C	Reuther (1973)
# days with 22 °C < Tavg < 25 °C	Kriedemann (1971)
# days with 25 °C < Tavg < 30 °C	Davies e Albrigo (1994)
# days with 20 °C < Tavg < 30 °C	Ribeiro et al. (2012)
# sprouting (270 °C day)	Aurambout et al. (2009); Catling, (1970).
# days with (R-ETP) > 0	Torres-Pacheco et al. (2013)
# days with (SW/SWHC) > 0,7	Torres-Pacheco et al. (2013)
# days with (SW/SWHC) > 0,5	Ramos et al., 2010
# days with R > 10 mm e R-ETP > 0	Torres-Pacheco et al. (2013)
# days with WD	Ramos et al., 2010
# days with WE	Ramos et al., 2010
# days of WE and # days of WD	Ramos et al., 2010
# days of WD and # days of WE	Ramos et al., 2010
# days with 16 °C < Tavg< 28 °C in 13 days	Lee et al. (2015)
WD and # days of WD	Ramos et al., 2010
WD/365	Ramos et al., 2010
# generations in the sprouting (96 °C day)	Soares-Colletti et al. (2016)
# days with Tmin > 13.5 °C e Tmax < 30 °C	Nava et al. (2007)
# days with Tmin > 18 °C e Tmax < 30 °C	Nava et al. (2007)
# days with Tmin > 10 °C e Tmax < 33 °C	Liu e Tsai (2000); Torres-Pacheco et al. (2013)
# days with Tmin > 16 °C e Tmax < 41 °C	Hall et al. (2011)
# days with 25 °C < Tavg < 28 °C	Liu e Tsai (2000)
# days with Tmin > 15 °C e Tmax < 32 °C	Moschini et al. (2010)
# days with Tmin > 18 °C e Tmax < 32 °C	Nava et al. (2007)
# days with 15 °C < Tavg < 25 °C	Liu e Tsai (2000)
# days with 70% < RHavg < 85%	Parra et al. (2010)
# generations psyllid (250 °C day)	Liu e Tsai (2000)
# generations psyllid (211 °C day)	Parra et al. (2010)
# days with WD ≥ 5 mm in 10 days and R ≥ 5mm in 5 days	Ramos et al. 2010; Davies e Albrigo (1994)
# days with WD ≥ 7 mm in 10 days and R ≥ 7 mm in 5 days	Ramos et al. 2010; Davies e Albrigo (1994)
# days with WD ≥ 10 mm in 10 days and R ≥ 10 mm in 5 days	Ramos et al. 2010; Davies e Albrigo (1994)
# days with WD ≥ 5 mm in 10 days and R ≥ 7 mm in 5 days	Ramos et al. 2010; Davies e Albrigo (1994)
# days with WD ≥ 5 mm in 10 days and R ≥ 10 mm in 5 days	Ramos et al. 2010; Davies e Albrigo (1994)

*Tavg: average air temperature; Tmax: maximum air temperature; Tmin: minimum air temperature; R: rainfall; WD: water deficit; WE: water excess; RHavg: Average relative humidity; ETP: potential evapotranspiration; #: number; SW: actual soil water; SWHC: soil water holding capacity; # days with: is a number of days with some condition; Acum: is a sum in a specific interval; °C day: is the unit for the thermal accumulation for completing the citrus sprout or a psyllid generation; # generations: is the number of generations for a given period based on the thermal time.

**Weather and weather-derived variables adapted from the literature.

In addition to the chosen parameters, others that showed good adjustment were the average temperatures between 15 to 32 °C and 15 to 25 °C, number of days with water deficit, number of days with water deficit divided by the number of days of the year and by the number of days with water excess, and finally water deficit events followed by precipitation. In the analysis, the parameters were combined to find the best fit and, thus, to obtain the model.

The development and calibration of the model was based on psyllid captures of five Brazilian farms for the growing seasons from 2015 to 2017. The performance of the model in this phase was evaluated by comparing observed and estimated psyllid captures per block. After that, the model was validated with independent data from 2015 to 2017 of other three farms in the state of São Paulo, Brazil, and with data from 2011 to 2019 of 53 farms in Florida, USA.

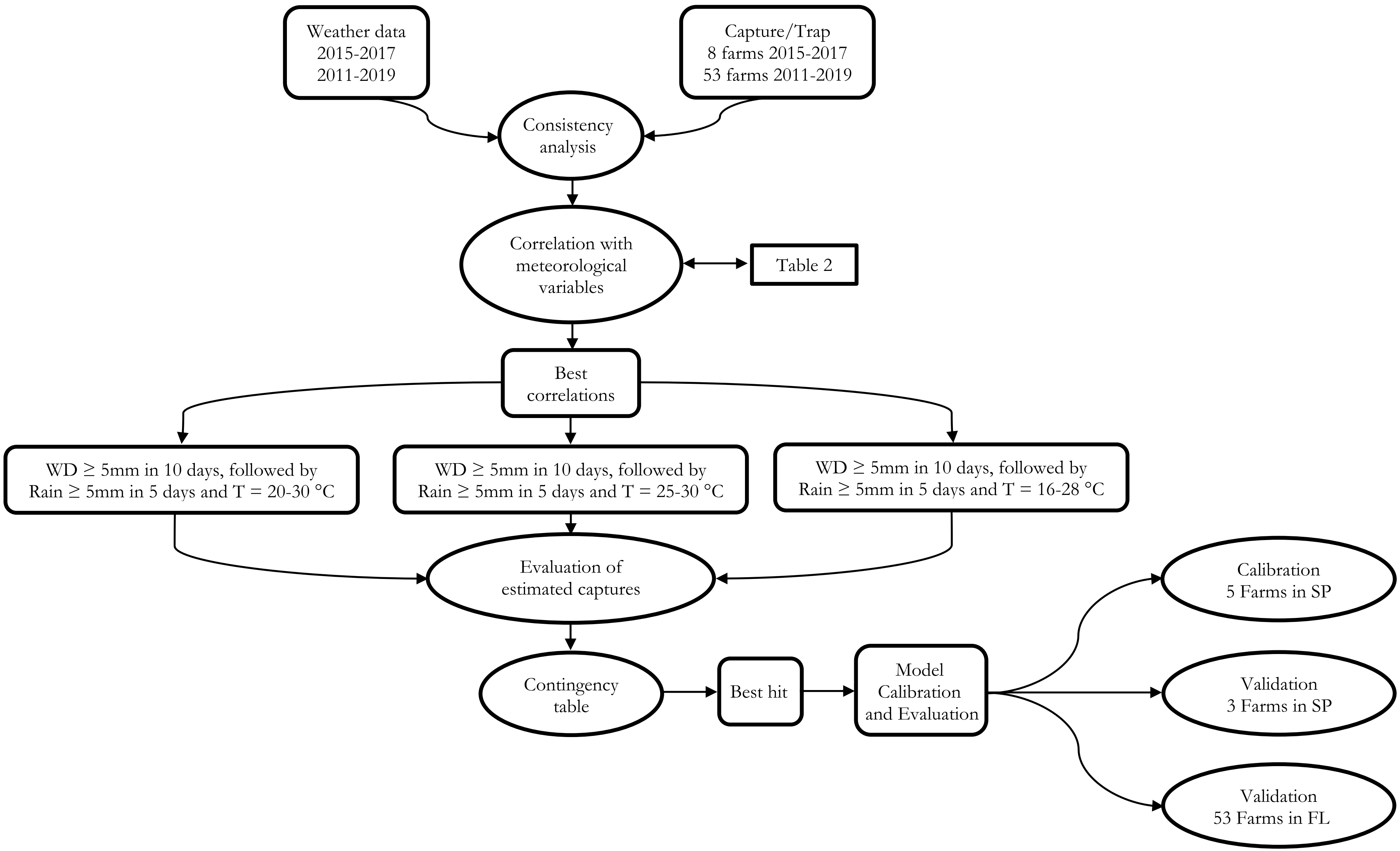

Figure 2. Flowchart of the procedures for modeling psyllid capture in orange orchards, using observed data from farms in the states of São Paulo, Brazil, and Florida, USA.

Figure 3 shows the decision tree for the start criterion for estimating the number of psyllid per block. Therefore, the models were based on the following conditions: water deficit (WD) greater than 5 mm accumulated in 10 days. Once this condition of WD occurs, there must have a rainfall of 5 mm in the next 5 days and at least four days with a favorable temperature conditions in the next seven days (Figure 3). The ranges of temperature tested were from 20 to 30 °C, from 25 to 30 °C, and from 16 to 28 °C, lower or higher temperatures are favorable to the occurrence of the psyllid. After that, the number of days under the favorable conditions in the last 14 days was computed, and then it was correlated with the number of psyllids captured per block, resulting in the models for estimating the number of psyllids per block during 7 days.

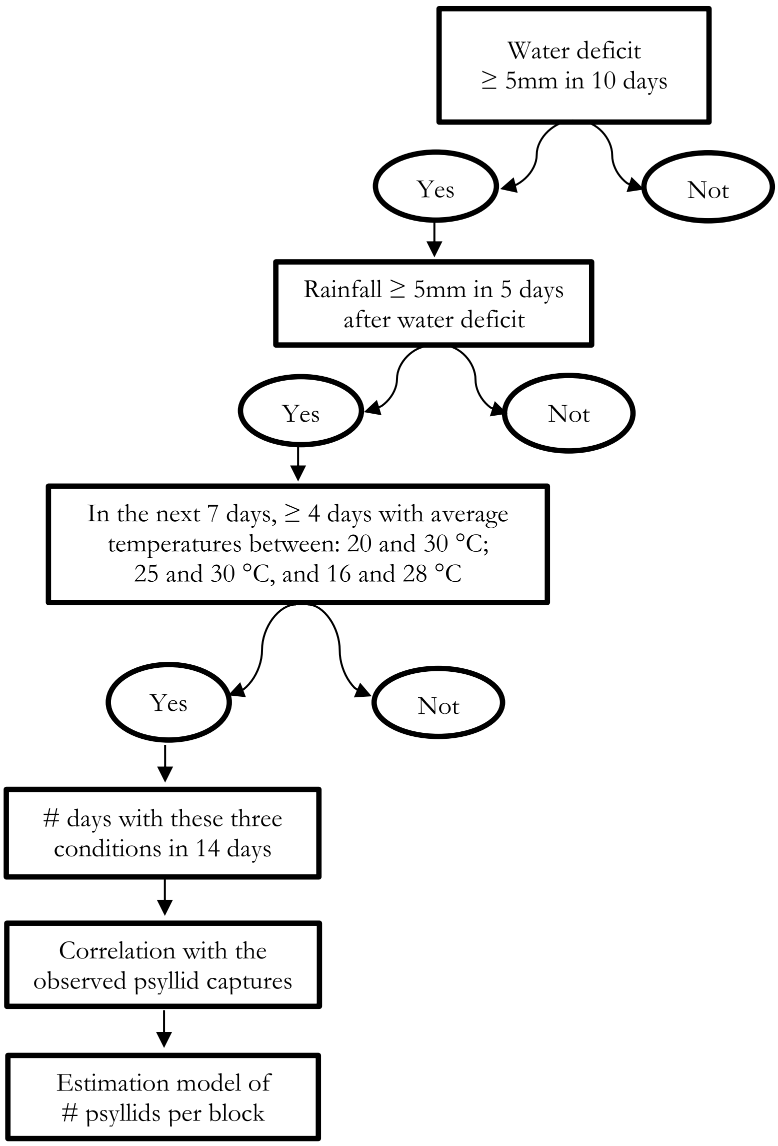

Figure 3. Flowchart for estimating the number of psyllids per block in orange orchards, based on the weather variables.

For the evaluation of best fitted model, during calibration and validation, estimated and observed psyllid captures were compared in a weekly basis and submitted to a statistical analysis using the contingency table for different levels of captures for applying the psyllid control (Table 2) (KIM et al., 2010). Regarding the thresholds used for psyllid captures, five scenarios were tested, very conservative (1 psyllid per block), conservative (2 psyllids per block), medium (3 psyllids per block), and little conservative (4 psyllids per block), also added the zero psyllid per block in the analysis. These scenarios represent the thresholds normally used for a spray decision making. The very conservative scenario is when the spray for psyllid control is based on only one capture per block, whereas the very little conservative requires at least four captures to start the spray for control.

Table 2. Contingency table used to evaluate the best fitted agrometeorological model for estimating the number of psyllids per block.

	Estimated (Above or equal)	**Estimated (Below)**
Observed (Above or equal)	Correct positive (X)	False negative (Y)
Observed (Below)	False positive (W)	Correct negative (Z)

X and Z denote correctness of the model; X represents when estimated number of psyllids is above or equal to the given threshold and agree with the observed data; Z represents when estimated number of psyllids is below the given threshold and agree with the observed data; Y and W represent errors in the model, being W the false positives or when estimated number of psyllids is above or equal to the given threshold while the observed number is below of that; and Y is when estimated number of psyllids is below the given threshold while the observed data is above or equal of that.

For the evaluation of the models at the different capture thresholds, the fraction of correct estimates (Fc), which is the correct positives (X) and negatives (Z) (Table 3) divided by the total of hits and errors (X+W+Y+Z) were used, with the results varying from 0 to 1, with 0 indicating that the model was not able to predict the level of psyllid captures and 1 indicates that the model correctly addressed the HLB vector captures in all cases (KIM et al., 2010). Equation 1 represents the calculation of Fc:

$$F_C = \frac{X+Z}{X+Y+W+Z} \qquad (1)$$

The proportion of correct positive (CP), correct negative (CN), false positive (FP) and false negative (FN) were calculated by dividing the number of estimates in each of them (X, Z, W, Y, respectively) by the total of hits and errors (X+W+Y+Z).

The bias (BS), which express the tendency of the estimates, was given by the relationship between the total of capture estimates above a given threshold (CP and FP) and the total of observed captures above the same threshold (Equation 2). The Bias represented the tendency of the model, when < 1 underestimated, >1 overestimated and equal 1 don't have tendency.

$$B_S = \frac{X+W}{X+Y} \tag{2}$$

In addition, a sensitivity analysis of the best models was performed by considering changes in their input parameters. The input parameters were systematically increased and decreased in 2°C for air temperature and in 20% for rainfall and compared to the number of psyllids per block with actual data. The aim of this analysis was to assess how much the models are able to identify the variations when applied in different locations.

2.3. Results

2.3.1. Meteorological data

The average weather conditions for the period from 2015 to 2017 on the farms located in the state of São Paulo, Brazil, are presented in Table 3. The average temperature is higher in January and February, varying from 25.0 to 26.3 °C, and after that, it decreases until reaching the minimum in June, ranging from 17.4 to 19.4 °C. The rainfall is higher during the summer, with January and February having between 170 and 249 mm per month, and lower during the winter months, June, July and August, with monthly rainfall ranging between 14 and 60 mm. Finally, the water deficit follows the rainfall seasonal distribution, with the highest values during the driest months, with values varying from 12 to 77 mm per month, whereas the wettest months normally present smaller water deficits, between 4 and 24 mm per month.

The average monthly air temperature in the farms in the state of Florida, USA, for the period between 2011 and 2019, vary seasonally, with the lowest values in January and the highest ones between June and August (Table 3). Monthly temperatures range from 14.1 to 28.6 °C in the 53 assessed farms. For rainfall, the highest values are observed from June to September, when the monthly amounts range between 136 and 345 mm. On the other hand, the lowest rainfalls are recorded from February to April, ranging from 27 to 73 mm per month. The water deficit is the opposite of precipitation, with lower values in the months of June to September, ranging from 1 to 34 mm per month, whereas the highest values are observed in the months between March and May, oscillating between 35 and 91 mm per month.

Table 3. Monthly average air temperature (T), rainfall (R) and water deficit (WD), calculated by the Thornthwaite and Mather (1955) water balance, in eight farms in the state of São Paulo, Brazil (2015-2017), and in 53 farms in the state of Florida, USA (2011-2019). The number of the farms in both states correspond to what is described in Figure 1.

Farm	Jan			Feb			Mar			Apr			May			Jun			Jul			Aug			Sep			Oct			Nov			Dec		
	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD
	(ºC)	(mm mo-1)		(ºC)	(mm mo-1)		(ºC)	(mm mo-1)		(ºC)	(mm mo-1)		(ºC)	(mm mo-1)		(ºC)	(mm mo-1)		(ºC)	(mm mo-1)		(ºC)	(mm mo-1)		(ºC)	(mm mo-1)		(ºC)	(mm mo-1)		(ºC)	(mm mo-1)		(ºC)	(mm mo-1)	
State of São Paulo, Brazil																																				
1	25.0	190	10	25.2	170	9	23.8	192	6	22.6	51	16	19.4	130	4	17.5	54	4	17.6	60	12	18.8	55	21	21.2	117	27	22.5	149	14	22.4	167	10	24.1	159	15
2	25.3	249	8	25.4	218	7	24.2	171	6	23.0	52	18	19.7	83	7	18.0	42	6	18.2	39	15	20.0	31	31	22.2	77	43	23.9	132	31	23.4	183	8	24.8	173	8
3	25.2	244	7	25.3	205	7	24.0	158	7	23.0	48	23	19.7	80	11	18.1	38	9	18.2	28	17	20.0	28	34	22.2	72	45	23.9	124	33	23.4	172	8	24.8	157	12
4	25.4	247	6	25.4	208	7	24.3	164	7	23.1	56	23	19.9	73	10	18.4	37	7	18.5	24	19	20.2	26	38	22.4	76	47	24.2	120	36	23.6	177	9	24.9	180	11
5	25.4	243	6	25.6	218	5	24.4	179	8	23.2	64	22	20.0	86	9	18.3	40	7	18.4	28	17	20.2	29	35	22.4	80	48	24.2	129	38	23.6	180	8	25.0	194	9
6	25.2	244	7	25.3	205	7	24.0	158	7	23.0	48	23	19.7	80	11	18.1	38	9	18.2	28	17	20.0	28	34	22.2	72	45	23.9	124	33	23.4	172	8	24.8	157	12
7	25.9	236	13	25.8	200	11	24.7	154	7	23.8	58	17	20.6	87	10	18.9	24	10	18.8	22	24	21.2	17	56	23.6	51	77	25.4	115	73	24.7	176	14	25.5	187	12
8	26.3	224	15	26.0	223	4	25.1	153	6	24.4	41	25	20.6	101	13	19.4	35	10	20.1	32	21	21.5	14	52	23.2	70	57	25.2	80	66	25.0	163	24	25.8	176	8
State of Florida. United Stated of America																																				
1	16.9	80	39	18.9	44	45	19.8	48	72	22.9	63	75	24.8	147	57	26.9	159	28	27.6	148	34	27.8	217	23	27.0	221	19	24.6	141	32	21.3	63	41	20.0	67	32
2	15.9	63	52	18.6	44	50	19.9	47	77	23.4	47	84	25.7	101	74	27.8	241	14	28.5	210	15	28.6	214	16	27.6	186	18	24.4	66	43	20.3	37	63	19.0	47	61
3	16.2	63	34	18.5	44	33	19.5	48	54	22.9	68	67	25.1	141	57	27.4	265	11	28.1	242	5	28.2	248	8	27.2	197	11	24.3	80	22	20.4	35	36	19.3	30	35
4	16.4	55	33	18.9	45	35	20.0	46	57	23.4	58	68	25.5	125	57	27.5	264	8	28.3	226	5	28.5	213	8	27.6	191	11	24.6	79	21	20.8	35	36	19.4	34	34
5	16.3	59	37	18.8	41	40	19.3	40	64	22.5	61	77	24.7	128	57	27.0	231	13	27.7	219	11	28.0	206	11	27.2	203	14	24.1	89	21	20.5	29	33	19.3	34	33
6	16.2	61	33	18.5	44	33	19.4	42	55	22.9	55	70	25.1	132	58	27.3	268	10	28.1	227	4	28.2	233	6	27.3	200	10	24.3	87	20	20.3	37	35	19.1	30	34
7	16.1	54	41	18.4	56	39	19.7	53	59	22.9	48	73	25.1	105	64	27.2	202	25	28.1	157	24	28.3	192	19	27.4	183	20	24.5	117	31	20.7	58	42	19.1	32	42
8	16.7	62	35	19.1	50	34	20.0	42	52	23.3	56	71	25.4	117	58	27.5	257	10	28.3	227	7	28.5	222	7	27.5	209	11	24.7	78	22	21.0	31	35	19.7	32	34
9	14.6	66	26	17.3	45	26	18.8	44	51	22.4	59	59	25.0	99	64	27.3	208	15	28.2	210	11	28.3	227	9	27.2	151	16	23.5	52	27	19.1	48	33	17.8	42	32
10	16.3	76	36	19.1	41	34	20.2	40	60	23.0	38	76	25.2	134	57	27.4	261	9	27.9	256	5	28.2	258	4	27.5	235	9	24.8	48	26	21.4	38	39	20.0	34	34
11	17.3	96	47	19.8	36	40	20.8	33	73	23.3	62	79	25.3	132	53	27.5	345	7	28.1	290	5	28.4	289	6	27.8	217	13	25.4	43	35	22.1	30	53	20.7	29	51
12	16.7	58	44	19.0	34	46	19.8	43	72	23.0	52	84	25.1	109	66	27.3	203	17	28.1	188	12	28.4	198	10	27.5	171	15	24.5	73	28	20.8	32	41	19.5	36	40
13	15.7	55	40	18.4	39	39	19.0	41	63	22.3	60	66	24.7	125	60	27.0	247	11	27.7	241	7	28.0	259	6	27.1	226	13	24.0	48	34	20.0	32	46	18.8	43	41
14	14.9	68	29	17.7	43	29	18.8	49	57	22.4	69	62	25.0	114	60	27.2	245	14	27.8	208	11	28.1	262	9	27.2	201	15	23.5	63	33	19.4	54	40	18.1	51	36
15	16.0	63	30	18.8	43	33	19.9	45	57	23.3	51	67	25.4	105	66	27.5	244	15	28.2	210	8	28.4	232	7	27.5	182	13	24.5	66	24	20.6	39	35	19.2	44	33
16	17.0	52	41	19.3	32	44	20.1	38	68	23.2	66	72	25.1	110	50	27.3	191	16	28.1	163	12	28.3	178	12	27.5	167	12	24.6	76	21	21.1	32	33	19.8	32	35
17	16.7	82	37	19.4	46	35	20.5	32	66	23.3	48	74	25.4	132	58	27.5	304	7	28.0	256	4	28.2	231	5	27.6	236	10	24.9	57	29	21.5	32	43	20.1	32	38
18	15.2	66	28	18.0	44	30	19.4	42	56	22.8	59	64	25.2	127	51	27.5	228	11	28.3	217	8	28.4	230	6	27.5	164	14	23.9	68	28	19.7	50	36	18.3	40	36

(Continue)

Farm	Jan			Feb			Mar			Apr			May			Jun			Jul			Aug			Sep			Oct			Nov			Dec		
	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD
	(°C)	(mm mo^{-1})		(°C)	(mm mo^{-1})		(°C)	(mm mo^{-1})		(°C)	(mm mo^{-1})		(°C)	(mm mo^{-1})		(°C)	(mm mo^{-1})		(°C)	(mm mo^{-1})		(°C)	(mm mo^{-1})		(°C)	(mm mo^{-1})		(°C)	(mm mo^{-1})		(°C)	(mm mo^{-1})		(°C)	(mm mo^{-1})	
19	17.0	75	39	19.6	40	36	20.7	28	66	23.4	54	71	25.4	120	61	27.5	266	9	28.1	252	4	28.3	252	4	27.6	206	9	25.1	52	25	21.8	32	36	20.3	26	38
20	16.3	56	33	18.7	44	34	19.8	48	59	23.3	49	72	25.4	119	68	27.5	269	10	28.2	206	7	28.4	219	9	27.6	186	10	24.4	80	22	20.4	36	37	19.2	38	33
21	16.4	72	30	18.2	50	31	19.1	36	60	22.4	62	72	24.5	133	53	26.9	197	17	27.7	179	17	28.1	196	15	27.0	195	16	24.2	116	27	20.8	59	32	19.4	48	27
22	16.7	75	32	18.6	39	36	19.4	45	62	22.4	55	70	24.4	152	49	26.8	175	21	27.6	187	17	27.9	205	12	27.0	217	11	24.3	133	22	21.0	43	33	19.6	40	30
23	16.7	54	36	19.0	36	39	19.7	35	64	23.0	50	78	25.0	114	55	27.2	206	12	28.0	170	10	28.2	210	8	27.4	191	9	24.5	75	23	20.9	34	34	19.6	36	31
24	16.5	66	35	18.9	50	33	19.8	45	51	23.2	65	67	25.2	124	54	27.5	254	10	28.2	262	5	28.3	243	6	27.4	207	10	24.5	77	23	20.8	31	35	19.5	27	36
25	15.9	61	29	18.5	46	30	19.7	51	54	23.1	57	59	25.3	98	61	27.4	247	13	28.1	220	7	28.3	215	8	27.5	171	12	24.3	57	26	20.3	36	37	19.0	47	33
26	16.6	62	36	18.9	37	37	19.8	41	61	23.0	46	76	25.1	109	64	27.4	231	13	28.1	191	8	28.3	206	8	27.4	174	12	24.5	81	22	20.8	29	35	19.5	35	34
27	16.2	62	42	18.7	42	40	19.3	40	66	22.5	42	82	25.1	129	67	27.2	230	17	27.9	248	6	28.3	276	7	27.4	215	12	24.4	56	33	20.3	32	49	19.2	42	45
28	16.1	58	30	18.7	48	33	19.9	47	56	23.3	46	68	25.4	108	62	27.5	245	11	28.2	222	6	28.4	212	8	27.6	181	10	24.4	71	22	20.5	39	34	19.2	40	32
29	16.1	66	37	18.4	42	34	19.1	40	60	22.5	57	72	24.7	118	66	27.0	246	14	27.7	210	9	27.9	257	8	27.1	189	14	24.1	82	24	20.2	27	36	19.1	26	38
30	16.0	66	31	18.4	39	33	19.3	43	58	22.6	51	73	24.9	107	68	27.2	230	14	27.9	217	5	28.1	245	5	27.3	205	10	24.1	79	20	20.1	38	34	18.9	34	34
31	17.3	30	37	18.6	28	27	21.6	36	51	24.1	73	35	25.1	72	42	27.1	147	8	27.8	150	4	28.4	136	4	27.5	167	1	24.9	30	16	21.8	34	22	19.9	6	35
32	16.2	32	33	17.6	41	34	19.7	48	51	23.4	53	57	25.2	83	48	27.2	211	12	28.0	196	6	28.3	197	9	27.3	175	6	24.0	77	23	20.1	34	39	18.3	18	32
33	14.1	69	21	16.8	50	22	18.4	47	44	22.1	59	54	24.7	105	55	27.1	196	18	28.0	207	11	28.1	180	9	26.9	147	14	23.1	49	27	18.6	52	31	17.4	48	26
34	16.1	63	37	18.5	40	34	19.3	37	60	22.6	58	70	24.9	125	60	27.1	217	13	27.7	191	8	28.0	262	6	27.2	185	11	24.2	66	22	20.3	28	36	19.1	29	40
35	16.0	62	33	18.5	38	35	19.3	42	59	22.7	47	71	25.0	112	68	27.2	256	13	27.9	194	9	28.1	244	6	27.3	195	9	24.2	67	24	20.2	39	34	19.0	45	34
36	17.1	89	36	19.6	38	34	20.8	32	63	23.5	55	72	25.5	116	55	27.6	311	7	28.1	270	4	28.3	286	4	27.7	229	9	25.2	51	23	21.9	31	36	20.5	26	38
37	16.5	58	42	18.7	37	43	19.4	39	70	22.5	50	83	24.4	120	57	26.8	206	14	27.7	150	14	27.9	210	12	26.9	172	14	24.1	98	25	20.7	40	35	19.3	31	36
38	15.9	59	32	18.2	49	33	19.3	36	59	22.6	53	75	24.7	111	62	27.0	204	14	27.9	177	9	28.2	192	8	27.3	196	11	24.0	83	19	20.4	50	34	19.0	33	32
39	16.2	64	38	18.7	38	36	19.5	46	60	22.7	45	74	25.0	119	66	27.2	234	17	27.8	216	8	28.0	237	6	27.2	204	11	24.3	71	22	20.5	31	35	19.3	24	38
40	16.2	65	35	18.5	45	33	19.4	35	58	22.7	58	73	24.9	116	61	27.2	248	12	27.9	212	6	28.2	250	5	27.3	185	13	24.2	63	25	20.3	36	36	19.1	26	37
41	17.2	81	40	19.8	33	37	20.8	27	70	23.4	47	85	25.2	118	57	27.4	240	12	28.1	235	7	28.3	223	8	27.7	195	11	25.2	64	26	22.0	27	42	20.5	27	42
42	17.2	83	40	19.9	39	36	20.9	28	68	23.4	32	91	25.2	122	59	27.5	247	11	28.3	247	8	28.4	231	8	27.8	190	12	25.4	68	25	22.2	27	41	20.7	29	42
43	15.5	64	25	18.0	49	26	19.4	50	43	22.9	71	51	25.2	97	53	27.5	219	15	28.3	196	13	28.5	201	11	27.5	187	13	24.1	93	19	20.1	46	28	18.6	38	28
44	17.4	73	43	19.9	44	40	20.8	37	61	23.4	59	71	25.2	122	55	27.5	276	7	28.1	218	5	28.4	229	6	27.9	215	14	25.5	44	31	22.2	29	45	20.8	22	47
45	15.6	58	36	18.2	39	37	19.0	45	59	22.6	58	65	24.9	107	67	27.0	237	15	27.6	224	8	27.9	238	9	27.2	179	15	23.9	51	35	19.9	42	45	18.7	46	39
46	15.5	57	30	18.1	43	31	19.5	47	55	23.0	57	63	25.4	108	60	27.6	222	16	28.4	197	11	28.5	220	10	27.6	172	15	24.1	72	25	20.0	41	37	18.7	41	35
47	17.1	77	47	18.9	34	50	19.7	47	76	22.6	66	79	24.5	152	58	26.9	170	20	27.8	169	22	27.8	198	17	27.1	204	18	24.3	106	35	21.2	53	45	19.8	44	43
48	17.2	73	35	19.1	39	37	19.8	40	61	22.8	61	74	24.6	127	55	26.9	202	12	27.8	150	17	28.0	202	13	27.1	183	10	24.5	107	21	21.3	44	33	19.8	41	32

(Conclusion)

Farm	Jan			Feb			Mar			Apr			May			Jun			Jul			Aug			Sep			Oct			Nov			Dec		
	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD	T	R	WD
	(ºC)	(mm mo^{-1})		(ºC)	(mm mo^{-1})		(ºC)	(mm mo^{-1})		(ºC)	(mm mo^{-1})		(ºC)	(mm mo^{-1})		(ºC)	(mm mo^{-1})		(ºC)	(mm mo^{-1})		(ºC)	(mm mo^{-1})		(ºC)	(mm mo^{-1})		(ºC)	(mm mo^{-1})		(ºC)	(mm mo^{-1})		(ºC)	(mm mo^{-1})	
49	16.8	69	36	18.8	39	38	19.5	42	64	22.6	57	73	24.4	143	53	26.8	194	14	27.7	174	11	27.9	210	9	27.0	205	11	24.2	116	21	21.0	40	33	19.6	39	31
50	16.0	57	37	18.5	40	35	19.2	35	60	22.5	48	75	24.8	114	64	27.0	215	14	27.7	182	10	28.1	236	7	27.2	178	12	24.2	51	27	20.3	31	38	19.0	38	38
51	17.6	77	43	20.2	37	39	21.2	30	69	23.5	42	86	25.2	120	59	27.6	251	13	28.4	244	5	28.7	226	9	28.1	207	12	25.7	54	27	22.6	29	44	21.1	26	44
52	14.7	73	21	17.1	48	22	18.6	44	44	22.2	73	55	24.5	111	48	27.1	199	17	28.0	191	14	28.1	192	13	27.0	171	11	23.5	96	15	19.4	49	23	17.9	39	25
53	15.7	55	39	18.4	36	39	19.2	42	61	22.7	54	68	24.8	115	63	27.1	229	13	27.7	218	8	28.0	229	8	27.3	213	15	24.1	48	33	20.1	36	46	19.0	47	41

2.3.2. Models for estimating the number of psyllids captured per block

Table 4 presents the models for estimating the number of psyllids captured per block in an interval of seven days, based on the weather conditions of the previous days, as presented in the footnote of the Table 4. Thus, the number of psyllids captured every 7 days can be estimated as a function of the number of favorable days, in the interval of 7 days, under the following specific conditions: WD ≥ 5 mm in the last 10 days; R ≥ 5 mm in the last 5 days, and T within the optimum range for the sprout estimated. The interval of time considered for the independent variables of the models (7 days) is in agreement with the period of residual effect of the products recommended for controlling of psyllids (AGROFIT, 2019). The performance of the three models at this phase of calibration was very good, with all of them presenting Fc average higher or equal than 95% (Table 4).

Table 4. Proposed models for estimating the number of psyllids captured per block as a function of weather conditions, considering an interval of captures of 7 days.

Model	Equations*	Average Fc (%)**
1	$Psyl./Bloc. = 0.4809 \times X1 + 1.9996$	96
2	$Psyl./Bloc. = 0.3403 \times X2 + 1.7944$	95
3	$Psyl./Bloc. = 0.3312 \times X3 + 1.7412$	95

*X1 = number of days in 14 days with water deficit ≥ 5mm in 10 days followed by rainfall ≥ 5mm in the next 5 days and air temperature between 25 and 30 °C in at least 4 out 7 days; X2 = number of days in 14 days with water deficit ≥ 5mm in 10 days followed by rainfall ≥ 5mm in the next 5 days and air temperature between 20 and 30 °C in at least 4 out 7 days; X3 = number of days in 14 days with water deficit ≥ 5mm in 10 days followed by rainfall ≥ 5mm in the next 5 days and air temperature between 16 and 28 °C in at least 4 out 7 days.

** Fc is the fraction of correct estimates.

2.3.3. Evaluation of models for estimating the number of psyllids per block in the state of São Paulo

To evaluate the models, the results of the contingency table and its analysis, presented in the Figure 4 and Table 5, were employed, admitting that the most important for psyllid control is to determine if the models can correctly estimate the number of psyllids per block above the thresholds considered. Supplementary material 1 at the end of the chapter contains yet another statistical evaluation comparing correct positives and correct negatives relation with observed data for obtaining of accuracy. The results follow the same trend as the values observed in Table 4. For model 1 (Table 4), similar accuracy was observed for both models´ calibration (Figure 4A) and validation (Figure 4B) phases. During the calibration phase, although the observed data showed greater variation (0 to 17), when compared to the estimates (0 to 8), the model presented a good accuracy for the five levels of capture, the same being observed in the validation, with Fc $\geq$ 0.915, but increasing from less than 1 to 4 psyllids captured per block (Table 5). In all models, when considering the capture threshold less than 1 psyllid per block, the correctness was 100% in the three assessed models (Table 5). Similarly, the model 2 (Table 4) showed variation in the distribution of the observed and estimated number of psyllids per block (Figures 4C and 4D). Although the results presented a good distribution, the estimated values were lower, which resulted in less errors and, consequently higher Fc, except for the threshold of 1 psyllid per block (Table 5). Model 3 (Table 4) presented a similar performance in relation to model 2 (Figures 4E and 4F), with a better Fc for the first threshold; however, for the other ones, its performance decreased a little bit, with a lower Fc than those obtained by models 1 and 2, for both calibration and validation phases (Table 5).

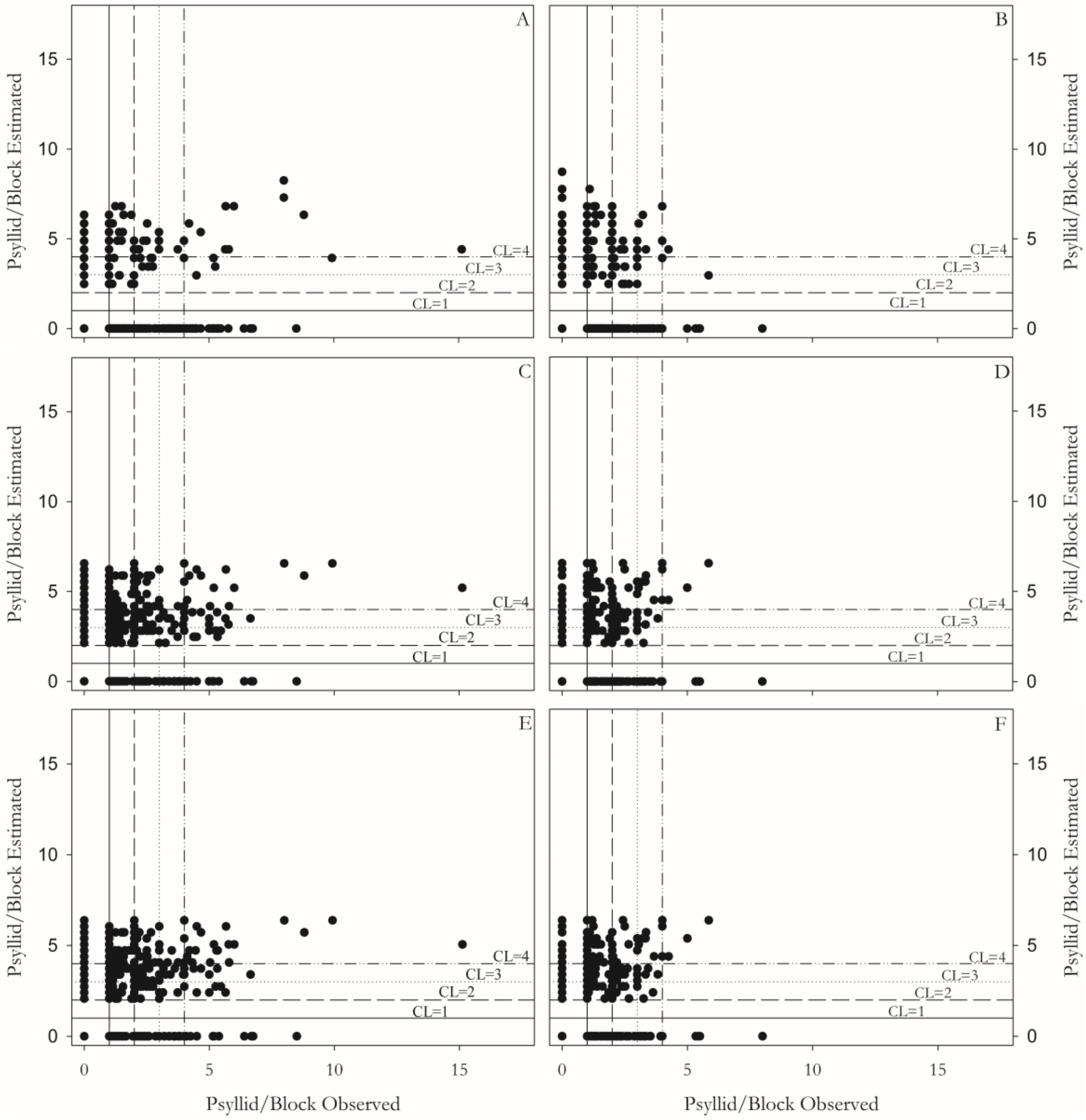

Figure 4. Relationship between observed and estimated number of psyllids captured per block in citrus orchards of the state of São Paulo, Brazil, during the models´ calibration (left) and validation (right), considering the following models: 1 - water deficit ≥ 5 mm in 10 days, followed by rainfall ≥ 5 mm in 5 days and air temperature between 25 and 30 °C in at least 4 out 7 days (A and B); 2 - water deficit ≥ 5 mm in 10 days, followed by rainfall ≥ 5 mm in 5 days and air temperature between 20 and 30 °C in at least 4 out 7 days (C and D); 3 - water deficit ≥ 5 mm in 10 days, followed by rainfall ≥ 5 mm in 5 days and air temperature between 16 and 28 °C in at least 4 out 7 days (E and F), for four thresholds: 1 Psyllid/Block; 2 Psyllids/Block; 3 Psyllids/Block; and 4 Psyllids/Block. The lines indicate the four control levels (CL) tested.

Table 5. Performance of the three models for estimating the number of psyllids per block during the calibration (Cal.) and validation (Val.) phases for five levels of capture thresholds in citrus orchards of the state of São Paulo, Brazil: Model 1 - water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 25 and 30 °C in at least 4 out 7 days; Model 2 - water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 20 and 30 °C in at least 4 out 7 days; and Model 3 - water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 16 and 28 °C in at least 4 out 7 days.

	Model 1		**Model 2**		**Model 3**	
	Calibration	**Validation**	**Calibration**	**Validation**	**Calibration**	**Validation**
Scenario Very Conservative Threshold (0 Psyllid/Block)						
C_N	0.000	0.000	0.000	0.000	0.000	0.000
F_P	0.000	0.000	0.000	0.000	0.000	0.000
F_N	0.000	0.000	0.000	0.000	0.000	0.000
C_P	1.000	1.000	1.000	1.000	1.000	1.000
F_C	1.000	1.000	1.000	1.000	1.000	1.000
B_S	0.000	0.000	0.000	0.000	0.000	0.000
Scenario Very Conservative Threshold (1 Psyllid/Block)						
C_N	0.897	0.896	0.889	0.888	0.888	0.887
F_P	0.008	0.008	0.016	0.016	0.017	0.017
F_N	0.078	0.073	0.051	0.047	0.044	0.046
C_P	0.017	0.024	0.044	0.049	0.052	0.050
F_C	0.915	0.920	0.933	0.937	0.939	0.937
B_S	1.077	1.072	1.039	1.035	1.029	1.032
Scenario Conservative Threshold (2 Psyllids/Block)						
C_N	0.944	0.943	0.923	0.920	0.916	0.918
F_P	0.016	0.020	0.037	0.044	0.044	0.046
F_N	0.031	0.026	0.018	0.015	0.016	0.015
C_P	0.009	0.011	0.022	0.021	0.024	0.022
F_C	0.953	0.954	0.945	0.941	0.940	0.939
B_S	1.015	1.005	0.979	0.970	0.970	0.968
Scenario Medium Threshold (3 Psyllids/Block)						
C_N	0.967	0.967	0.948	0.946	0.942	0.943
F_P	0.015	0.021	0.034	0.042	0.040	0.046
F_N	0.014	0.008	0.010	0.005	0.008	0.005
C_P	0.004	0.003	0.008	0.007	0.010	0.007
F_C	0.972	0.971	0.956	0.953	0.952	0.950
B_S	0.999	0.987	0.975	0.962	0.967	0.959
Scenario Little conservative Threshold (4 Psyllids/Block)						
C_N	0.978	0.981	0.970	0.971	0.965	0.969
F_P	0.011	0.016	0.019	0.026	0.024	0.028
F_N	0.008	0.002	0.007	0.002	0.006	0.002
C_P	0.003	0.001	0.004	0.002	0.005	0.002
F_C	0.981	0.982	0.973	0.973	0.969	0.971
B_S	0.997	0.987	0.988	0.976	0.981	0.973

CN: Correct negative; FP: False positive; FN: False negative; CP: Correct positive; FC: Fraction of correct estimates and BS: Bias.

In the calibration phase, the model with the highest accuracy in the most conservative scenario (one psyllid per block) was Model 3, with a Fc = 0.939. This model was also the one with the highest correct positive (C_P) for all thresholds, what was expected since this is the threshold that allowed the highest number of captures above it. The false positive (F_P), that represents the capture above the thresholds when it does not happen, was higher in this model, but the false negative (F_N) was lower than the other models. This condition was maintained for the scenarios with the thresholds of 2, 3 and 4 psyllids captured per block. Finally, both in the calibration of the models and their validation, no expressive tendency of under or overestimation was observed, with Bias always close to 1.

In general, the model with the best performance, with the highest C_P and the smallest F_N, was Model 3, which combines water deficit and rainfall conditions with the favorable air temperature for psyllids development between 16 and 28 °C (Table 5).

Regarding the number of psyllids captured per block in each farm, those located further south in the state of São Paulo presented lower number than those in the center of the state (Figure 5A). The southernmost farm, in Itapetininga (1), is the one with the lowest HLB vector captures, while the ones upper north, as Ibitinga (7) and Reginópolis (8), had the highest average captures (Figure 5A). Regarding the number of psyllids per block estimated by the model 3, farms located in the north-central region of the state, represented by locations 3, 6, 7 and 8 in Figure 5, were those with the highest average number of psyllids per block (Figure 5B).

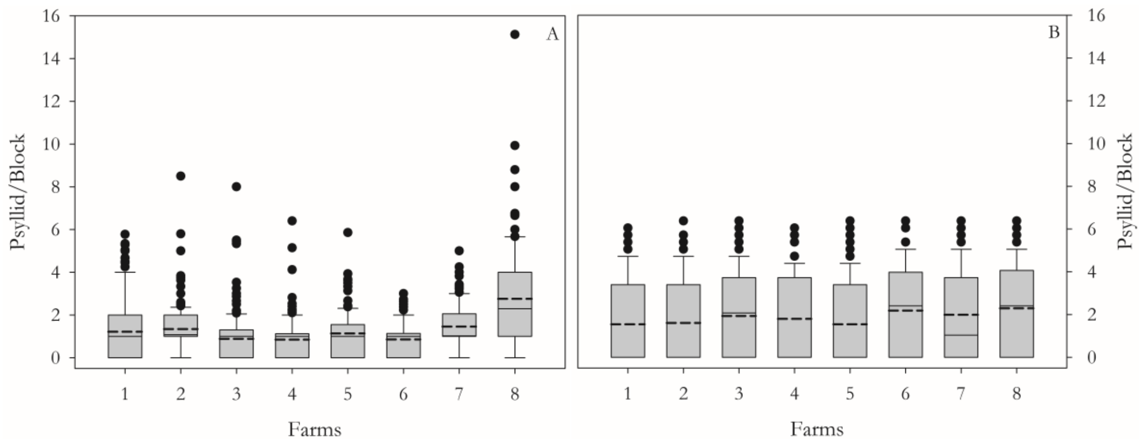

Figure 5. Number of psyllids per block observed in the farms (A) and estimated by the model 3, based on water deficit and rainfall conditions and air temperature between 16 to 28 °C (B), in eight farms located in the state of São Paulo, Brazil: Itapetininga (1); Botucatu (2); Anhembi (3); Piracicaba (4); Botucatu (5); Bauru (6); Ibitinga (7); and Reginópolis (8). The dotted lines indicate the average.

The sensitivity analysis of the proposed models for estimating the number of psyllids per block demonstrated variability in the results in the two assessed locations, being one in the south and another in the center-north of the State of São Paulo (Figure 6). Considering the model 1, based on water deficit and rainfall conditions for estimated citrus sprouting combined with the temperature interval of 25 to 30 °C (Figures 6A and 6B), it is possible to observe a greater sensitivity of the model to the most southern location, compared to the north-center one, in which an increase of 2 °C, a decrease of 2 °C and an increase and decrease of 20% in rainfall were tested. For

Itapetininga (Figure 6A), further south, a decrease of 2 °C reduced the number of psyllids. On the other hand, an increase of 2 °C resulted in an increase of the psyllid captures. Similar results were found when changes in rainfall of -20% and +20% were simulated. For the northernmost farm, in Reginópolis (Figure 6B), an increase of 2 °C in temperature and a decrease of 20% in rainfall resulted in an increase in the number of psyllids captured per block, with the opposite being observed when the temperature was decreased by 2 °C and rainfall was increased by 20 %.

When the model based on water deficit and rainfall conditions together with the temperature range of 20 to 30 °C (Model 2) was used, the results showed that it had less sensitivity to changes in the input variables in both assessed locations (Figures 6C and 6D). For Itapetininga (Figure 6C), with a temperature increase of 2 °C and 20% decrease in rainfall, the number of psyllids per block increased, like what was observed for the current temperature with a 20% increase in precipitation and decreases with a decrease at 2 °C of temperature. In Reginópolis (Figure 6D), the number of psyllids per block increased when temperature was raised by 2 °C and rainfall was decreased by 20%. For the other changes, the model generated little differences in relation to the current conditions.

Finally, model 3, based on water deficit and rainfall conditions associated to the air temperature ranging between 16 and 28 °C, was the least sensitive to changes in the weather conditions for Itapetininga (Figure 6E), whereas for Reginópolis (Figure 6F), the number of psyllids per block was higher under lower temperatures (decrease of 2 °C) and with less 20% in rainfall. When the temperature and rainfall were increased, the number of psyllids per block remained close to the current condition.

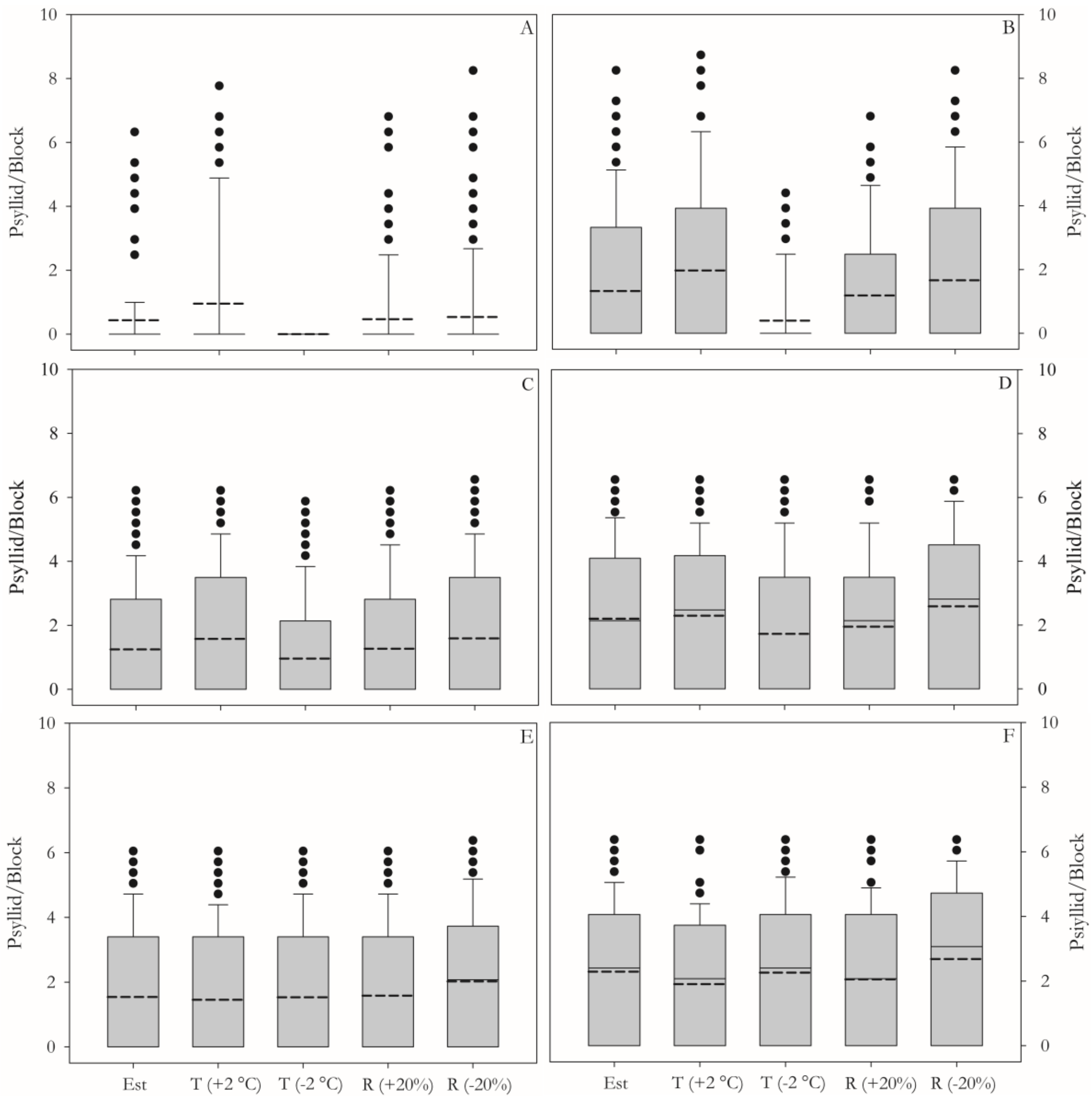

Figure 6. Sensitivity analysis of the models for estimating the number of psyllids per block: Model 1 - based on water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 25 and 30 °C in at least 4 out 7 days (A and B); Model 2 - based on water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 20 and 30 °C in at least 4 out 7 days (C and D); and Model 3 - based on water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 16 and 28 °C in at least 4 out 7 days (E and F) for Itapetininga (A, C and E) and Reginópolis (B, D and F), state of São Paulo, Brazil, considering changes in air temperature of -2 °C and +2 °C, and in rainfall of -20% and +20%. The dotted lines indicate the average.

2.3.4. Monthly assessment of occurrence of the psyllid for the state of São Paulo

Considering the monthly dynamic of the HLB vector observed between 2015 to 2017 for the assessed farms of the state of São Paulo (Figure 7D) compared to the estimates by the proposed models (Figure 7A, 7B and 7C), one can see that there are expressive differences. However, when considering the captures of psyllids per block throughout the year, observed data as well as the models show that highest values happen in the spring and summer months. Another aspect to be highlighted is that the observed data vary in a higher amplitude than the estimates, besides the percentage of correctness of the model is high (Table 5). The model based on water deficit and rainfall conditions combined with a temperature range of 25 to 30 °C (Model 1) estimated only captures during the period from September to April. The models based on water deficit and rainfall conditions together with the temperature ranges of 20 to 30 °C (Model 2) or 16 to 28 °C (model 3), presented a similar captures variability among farms along the year, with highest average values occurring from September to April. When the observed data was evaluated, they are also reported captures during all months of the year, with the highest values from August to December, when the peak occurs, mainly in September and November (Figure 7D).

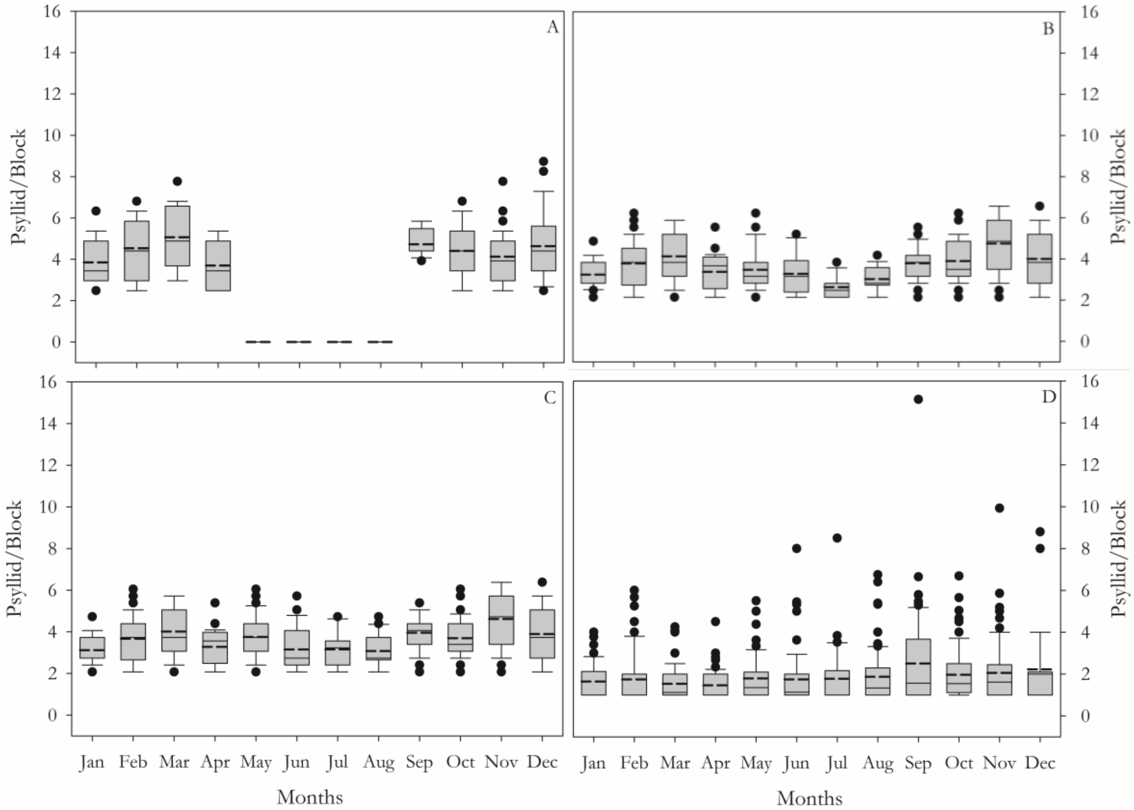

Figure 7. Monthly variability of psyllids captured per block estimated by the agrometeorological models that consider: water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 25 and 30 °C in at least 4 out 7 days (Model 1 - A); water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 20 and 30 °C in at least 4 out 7 days (Model 2 - B); water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 16 and 28 °C in at least 4 out 7 days (Model 3 - C), and observed (D) for the eight farms in the state of São Paulo, in the period from 2015 to 2017. The dotted lines indicate the average.

2.3.5. Evaluation of the model for estimating the number of psyllids per block in the state of Florida

Table 6 presents the contingency analysis for the psyllid capture estimations in the state of Florida, USA, using the model developed and validated for the farms in the state of São Paulo. The fraction of correct (F_C) estimates was higher when the model was run every 21 days compared to every 7 days, and in both cases, F_C was higher when the capture threshold of less than 1 psyllid per block was considered, decreasing for the other thresholds. As observed in the state of São Paulo (Table 5), in the state of Florida (Table 6) the capture threshold less than 1 psyllid per block presented 100% of correctness for the two intervals of the model, 7 and 21 days. The number of false negatives (F_N), which is when the model estimates a capture below the threshold and it was above, was null for the time step of 21 days for 1 psyllid per field block and increasing up to 4 psyllids per block. When the model was applied for the time step of 7 days, the number of F_N was higher for 1 psyllid per block threshold, however it decreased with the increase of the thresholds. The fraction of correct positives (C_P), when the model estimated a capture above the threshold and it occurred, was higher in the most conservative scenario (1 psyllid per block) and decreased in the less conservative scenarios for both time steps. For the 7-day interval, the false positive (F_P), which represents when the model estimated captures above the threshold and they do not occur, was very low, following the same tendency of F_N, with lower values for 1 psyllid per block threshold and increasing up to 4 psyllids per block. For the 21-day interval, F_P decreased as the threshold of number of psyllids per block increased. The model bias (BS) presented an opposite tendency between the time steps, with the 21-day time step overestimating captures for 1 psyllid per block and underestimating for the other thresholds. On the other hand, for the 7-day time step, the opposite was observed (Table 6). Supplementary material 2, at the end of this chapter, presents a statistical evaluation comparing correct positives in relation to correct and incorrect positives, the same being carried out with negative values, and the correlation between the two parameters for obtaining accuracy.

Table 6. Performance of model 3, which is based on the water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 16 and 28 °C in at least 4 out 7 days, for estimating the number of psyllids captured per block during the calibration and validation phases for five levels of capture thresholds in the farms in state of Florida, USA, considering two time-steps for estimations (21 and 7 days).

Scenario	Statistical parameters	Time step	
		21 days	7 days
0 Psyllid/Block Very conservative	C_N	0.000	0.000
	F_P	0.000	0.000
	F_N	0.000	0.000
	C_P	1.000	1.000
	F_C	1.000	1.000
	B_S	1.000	1.000
1 Psyllid/Block Very conservative	C_N	0.954	0.881
	F_P	0.008	0.031
	F_N	0.000	0.032
	C_P	0.038	0.056
	F_C	0.992	0.937
	B_S	1.200	0.983
2 Psyllids/Block Conservative	C_N	0.959	0.892
	F_P	0.007	0.049
	F_N	0.012	0.021
	C_P	0.022	0.038
	F_C	0.981	0.930
	B_S	0.858	1.475
3 Psyllids/Block Medium	C_N	0.963	0.903
	F_P	0.008	0.056
	F_N	0.015	0.016
	C_P	0.015	0.024
	F_C	0.978	0.928
	B_S	0.755	2.000
4 Psyllids/Block Little conservative	C_N	0.970	0.913
	F_P	0.005	0.057
	F_N	0.018	0.013
	C_P	0.007	0.017
	F_C	0.977	0.930
	B_S	0.471	2.476

CN: Correct negative; FP: False positive; FN: False negative; CP: Correct positive; FC: Fraction of correct estimates and BS: Bias.

Considering the thresholds of four psyllids captured per block and the two-time steps, the observed data showed a greater magnitude when compared to the estimated data, as presented in Figure 8. Although the model for both time steps estimated psyllid captures smaller than observed (Figure 8), the Fc was high (Table 6). For the 21-day time step, the observed data have a maximum capture of 164 psyllids per block the estimated captures had a maximum of 6 psyllids per block. For the time step of 7 days, the observed data showed a maximum of 57 psyllids per block while the estimated values reached a maximum of 6 psyllids per block.

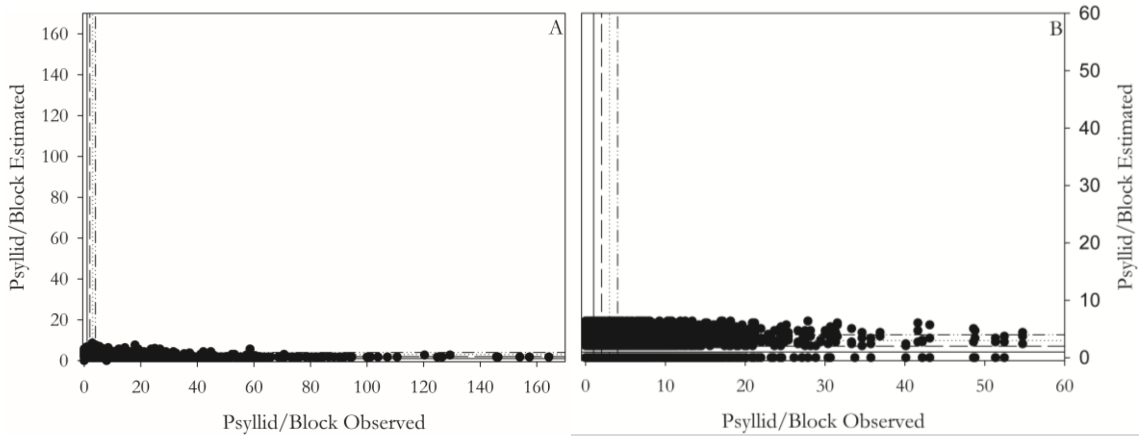

Figure 8. Relationship between observed and estimated number of psyllids captured per block, when employing the Model 3 (water deficit ≥ 5 mm in 10 days, followed by rainfall ≥ 5 mm in 5 days and air temperature between 16 and 28 °C in at least 4 out 7 days), considering two time steps (21 days - A, and 7 days - B) and four thresholds (1 Psyllid/Block, 2 Psyllids/Block, 3 Psyllids/Block and 4 Psyllids/Block). The lines indicate the four control levels (CL) tested.

The captures of psyllids obtained in Florida (Figure 9) are much higher than those observed in Brazil (Figure 4). Although the traps were collected in a different period, every 21 days in the United States and every 7 days in Brazil, when the data were converted to 7-day interval, the differences remained high. Even with such differences, the results obtained here reflect them, with much more psyllid captures in Florida than in Brazil, which is caused, basically, by the more favorable climatic conditions for psyllid development in this American state.

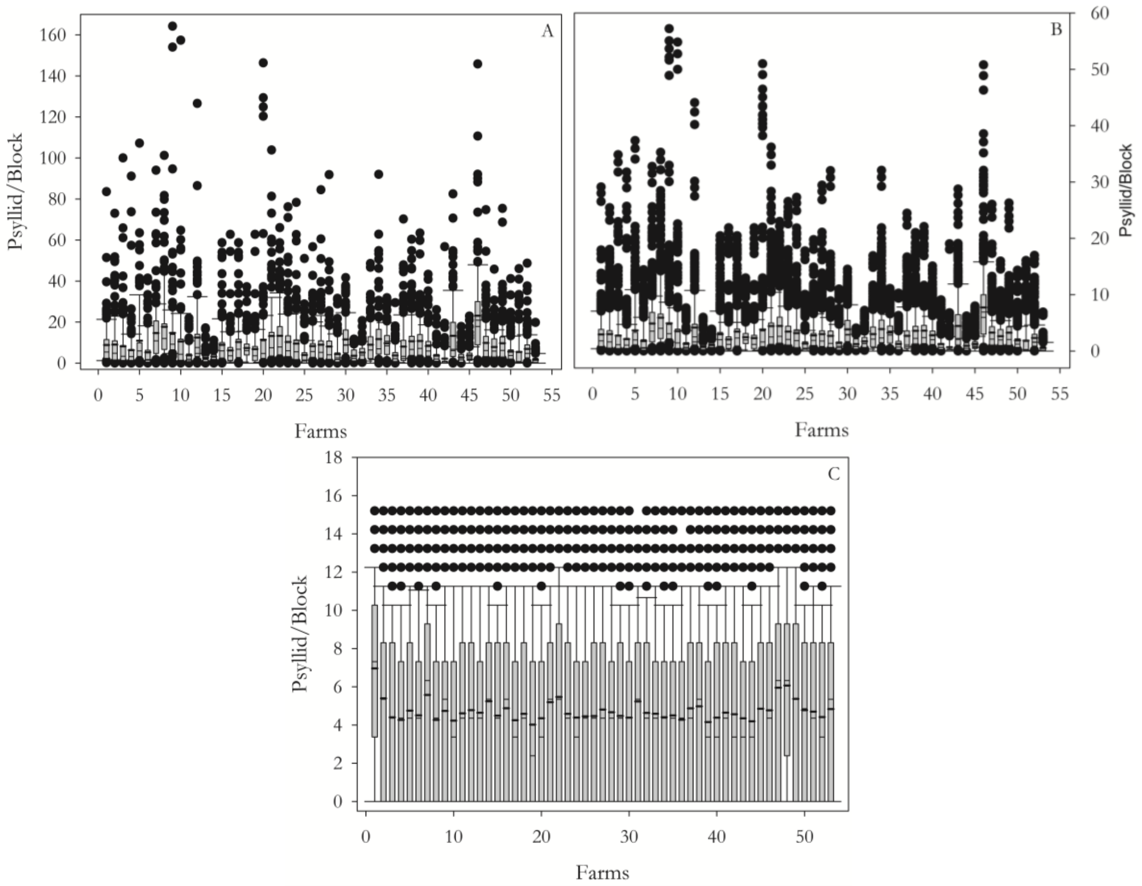

Figure 9. Number of psyllids per block observed in the 53 farms in the state of Florida, USA, every 21 days (A) and 7 days (B) and estimated by the Model 3 (C) based on water deficit ≥ 5 mm in 10 days, followed by rainfall ≥ 5 mm in 5 days and air temperature between 16 and 28 °C in at least 4 out 7 days. The number of the farms in the X-axis correspond to what is described in Figure 1. The dotted lines indicate the average.

2.3.6. Monthly assessment of psyllid occurrence for the state of Florida

Regarding the estimated monthly capture of psyllids, it varies throughout the year (Figure 10A), with lower average captures from September to May, and highest ones from June to August. Regarding the observed data, they are higher from March to August, during the spring and summer, and lower in the other months, for both 21-day and 7-day time steps (Figure 10B and 10C).

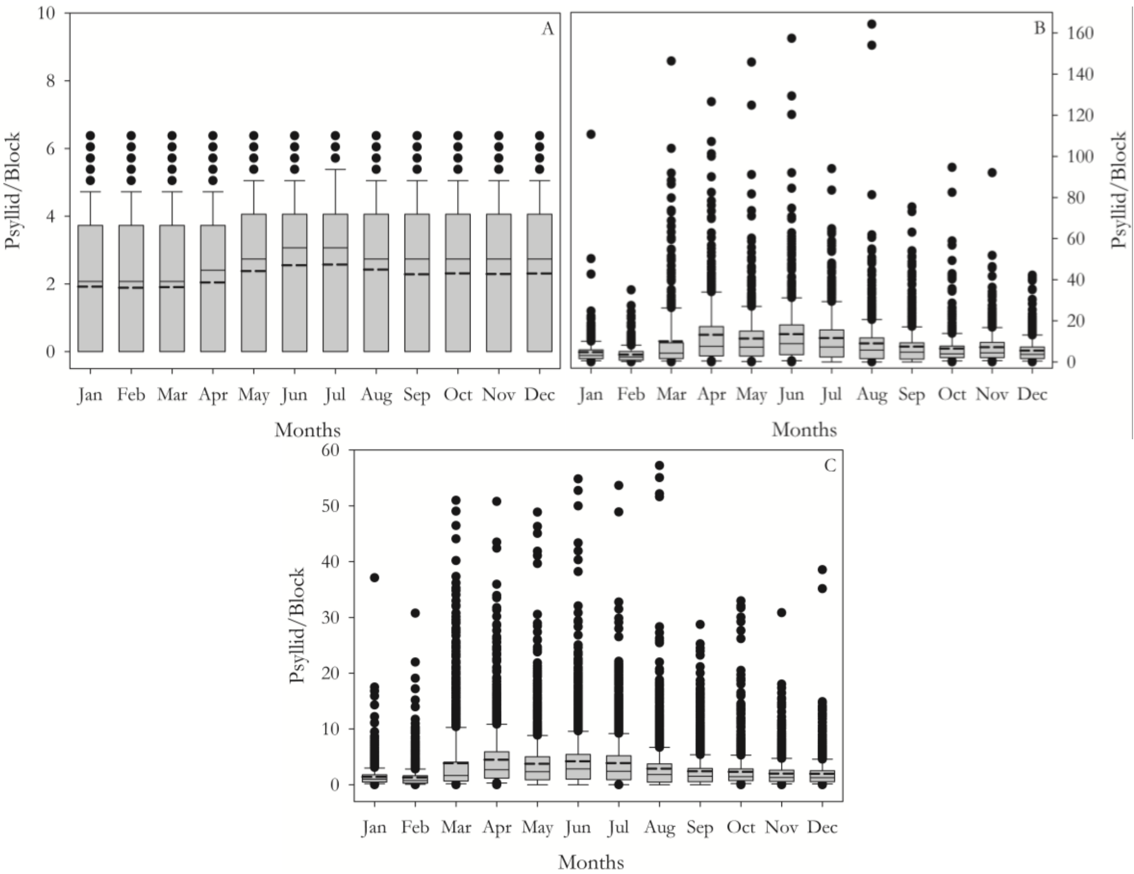

Figure 10. Monthly variability of psyllids captured per block estimated by the agrometeorological models that consider water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 16 to 28 °C in at least 4 out 7 days estimated every 7 days (A), observed in a 21-day time step (B), and in a 7-day time step (C), for the 53 farms in the state of Florida, USA, for the period between 2011 and 2019. The dotted lines indicate the average.

2.4. Discussion

The models that estimated the number of psyllids captured per block are based on the occurrence of estimated citrus sprouts, which is the most attractive phase for the growth of HLB vector population. According to Parra et al. (2010), at this stage, the psyllids oviposit in new branches, which allows it to increase its population in the area. According to Ramos et al. (2010), water deficit events followed by rainfall are the main drivers for citrus sprouting. Allied to this, it is also required favorable temperatures for citrus sprouting, which can range from 16 to 30 °C, varying among different references: 20 to 30 °C (RIBEIRO et al., 2012); 25 to 30 °C (DAVIES; ALBRIGO, 1994); and 16 to 28 °C (Lee et al., 2015).

The model for estimating the captures of HLB vector is not based on the temperature of psyllid development, once it can survive and develop under a wide range of temperature (10 to 41 °C), as reported by several authors: 13.5 to 30 °C (NAVA et al., 2007); 10 to 33 °C (LIU; TSAI, 2000; TORRES-PACHECO et al., 2013); and 16 to 41 °C (HALL et al., 2011). These temperatures occur throughout most of the year in the citrus producing regions of the state of São Paulo, Brazil, as well as at Florida, USA (Table 1), which makes the weather conditions that affect estimated citrus sprouting more relevant than those for the psyllid.

The psyllid capture model, based on estimated citrus sprouting, was based on the water deficit and rainfall conditions to start the process and then on temperature since it has effect on the availability and duration of the newly formed sprouts. As reported by Aurambout et al. (2009), with higher temperatures, the sprouts become less tender in a short period, which ends up limiting the ideal conditions for the psyllid's development. Ribeiro et al. (2012) found greater growth of the aerial part of citrus in conditions of temperatures ranging between 20 and 30 °C when compared to the range of 20 to 25 °C, showing that air temperature affects the time of young branches availability and, consequently, the occurrence of the HLB vector. The psyllid capture model based on water deficit and rainfall conditions that favor the development of citrus sprouts combined with an average temperature of 16 to 28 °C was the one that presented the best accuracy in most of the assessed scenarios (Table 5). This range of temperature refers to the citrus development (LEE et al., 2015); however, according to Nava et al. (2007), it is also close to the optimal temperature interval for the development of eggs and nymphs of the psyllid (18 to 30 °C). Therefore, the temperature range used in the best fitted model was favorable for both citrus sprouting and psyllid´s development. Nava et al. (2007) found greater viability of psyllids at temperatures between 18 to 30 °C. Temperatures above 32 °C were unfavorable to psyllid´s development. These results agree with the range of temperature most suitable for citrus sprouting and psyllid capture used in the proposed model. On the other hand, Narouei-Khandan et al. (2016) found that at temperatures above 25 °C the population of psyllids normally decreases, which is not totally aligned with the results of the present study, that found a positive correlation between psyllids capture and the number of days with temperature between 16 and 28 °C.

Diaz-Padilla et al. (2014) found that HLB vector development is affected by lower temperatures, which is in line with what was observed in this study, in which upper north farms had a greater number of estimated psyllids than the ones located in the center-south of the state of São Paulo. Another aspect to be considered is that at the southernmost farms the sprouting were distributed along the year since the rainfall in this region in better seasonally distributed, whereas at the farms in the north the drier winter allows a concentration of the sprouts just after the first expressive rainfalls. Similar results were found by Torres-Pacheco et al. (2013), who found that the greatest favorability for the emission of citrus sprouts occurred during the beginning of rainy season in northern Mexico. On the other hand, in the south, where is predominantly wet all year long, the emissions of new tissues are frequent, favoring psyllid attack.

If from one side rainfall is an important driver for HLB vector find new tissues to oviposite, on the other one excessive rainfall, greater than 150 mm per month, tends to be detrimental to the growth of the vector´s population, as such conditions remove eggs, nymphs, and adults from the plants, decreasing the bacterium transmission (MOSCHINI et al., 2010).

To develop the proposed model (Table 5), the interval for captures of seven days was used, which is compatible with the residual effect of the insecticides used for psyllid control. According to Assato (2018), the interval between spraying over 13 days was not efficient for controlling HLB vector. This author recommends spraying the orchards with a shorter interval of time, since both nymphs and adults can acquire and transmit the bacteria in only 6 to 7 days (NAVA et al., 2007; CANALE et al, 2016). According to Nava et al. (2007) and Parra et al. (2010), the fourth and fifth instars of the psyllid nymphs are those more favorable for the acquisition of the bacterium, presenting an average duration of seven days, whereas the approximate duration of the five instars is of 15 days (NAVA et al., 2007). In addition, citrus sprouts are no longer considered young after 13 days under temperatures between 16 to 28 °C (LEE et al., 2015). As the model that presented the best performance (Table 5) was the one with an interval time of capture of 7 days, in which 4 days under favorable conditions makes the citrus plants to sprout, the proposed model can be considered as suitable for estimating HLB vector population growth and, therefore, be used as an aid in decision support systems psyllid control.

2.5. Conclusion

The model based on water deficit, followed by rainfall and average air temperature between 16 to 28 °C, was the one with the best performance for estimating the number of psyllids captured per block in orange orchards in states of São Paulo, Brazil, and Florida, USA, both with more than 90% of correct hits. This model also showed to be sensitive the weather parameters used as inputs. Based on the consistent results presented here, the proposed agrometeorological model can be used as an important tool to assist the orange growers in Brazil and USA in their decision-making regarding psyllid control aiming to reduce damages caused by HLB disease.

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SUPPLEMENTARY MATERIAL

Supplementary Material 1. Performance of the three models for estimating the number of psyllids per block during the calibration and validation phases for five levels of capture thresholds in citrus orchards of the state of São Paulo, Brazil: Model 1 - water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 25 and 30 °C in at least 4 out 7 days; Model 2 - water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 20 and 30 °C in at least 4 out 7 days; and Model 3 - water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 16 and 28 °C in at least 4 out 7 days.

	Model 1		**Model 2**		**Model 3**	
	Calibration	**Validation**	**Calibration**	**Validation**	**Calibration**	**Validation**
Scenario Very Conservative Threshold (0 Psyllid/Block)						
CP*	1.000	0.000	1.000	0.000	1.000	0.000
CN	0.000	0.000	0.000	0.000	0.000	0.000
Accuracy	0.500	0.500	0.500	0.500	0.500	0.500
Scenario Very Conservative Threshold (1 Psyllid/Block)						
CP	0.184	0.246	0.465	0.511	0.542	0.524
CN	0.991	0.992	0.983	0.983	0.981	0.981
Accuracy	0.588	0.619	0.724	0.747	0.761	0.752
Scenario Conservative Threshold (2 Psyllid/Block)						
CP	0.226	0.300	0.558	0.583	0.611	0.592
CN	0.983	0.979	0.961	0.955	0.954	0.952
Accuracy	0.605	0.639	0.759	0.769	0.782	0.772
Scenario Medium Threshold (3 Psyllid/Block)						
CP	0.233	0.289	0.453	0.579	0.558	0.579
CN	0.985	0.979	0.965	0.957	0.959	0.954
Accuracy	0.609	0.634	0.709	0.768	0.759	0.766
Scenario Little Conservative Threshold (4 Psyllid/Block)						
CP	0.235	0.273	0.333	0.545	0.431	0.545
CN	0.989	0.984	0.980	0.974	0.975	0.972
Accuracy	0.612	0.628	0.657	0.760	0.703	0.759

* CP – Correct Positive – relation with the correct positive divided to false negative;

CN – Correct Negative – relation with the correct negative divided to false positive;

Accuracy - Average Correct positive and correct negative.

Supplementary Material 2. Performance of model 3, which is based on the water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in 5 days and air temperature between 16 and 28 °C in at least 4 out 7 days, for estimating the number of psyllids captured per block during the calibration and validation phases for five levels of capture thresholds in the farms in state of Florida, USA, considering two time-steps for estimations (21 and 7 days).

		Time step	
		21 days	**7 days**
0 Psyllid/Block Very conservative	**CP***	1.000	1.000
	CN	0.000	0.000
	Accuracy	0.500	0.500
1 Psyllid/Block Very conservative	**CP**	1.000	0.634
	CN	0.992	0.966
	Accuracy	0.996	0.800
2 Psyllid/Block Conservative	**CP**	0.640	0.640
	CN	0.992	0.948
	Accuracy	0.816	0.794
3 Psyllid/Block Medium	**CP**	0.499	0.604
	CN	0.992	0.941
	Accuracy	0.745	0.773
4 Psyllid/Block Little conservative	**CP**	0.291	0.563
	CN	0.995	0.941
	Accuracy	0.643	0.752

* CP – Correct Positive – relation with the correct positive divided to false negative;

CN – Correct Negative – relation with the correct negative divided to false positive;

Accuracy - Average Correct positive and correct negative.

3. AGROCLIMATIC RISK OF ASIAN CITRUS PSYLLID OCCURRENCE IN THE MAIN PRODUCING REGIONS OF BRAZIL AND USA

ABSTRACT

Brazil and part of the south and southeast of the United States of America (USA) are among the regions of the world with the best conditions for citrus production. However, in these two countries, producers are facing substantial production challenges due to the occurrence of diseases. Currently, the most important disease for citrus cultivation, nationally and worldwide, is huanglongbing (HLB), which has required the eradication of millions of trees from citrus orchards. This bacterial disease is transmitted by the psyllid *Diaphorina citri*; the causal agent is a phytoplasma named *Candidatus* Liberibacter asiaticus. Given the great influence that meteorological conditions have on the dynamics and dispersion of the psyllid population, the objectives of this study were to determine monthly and annual climatic risks of occurrence of the Asian psyllid in the main citrus producing regions of Brazil and the USA, through a calibrated and validated agrometeorological model, which estimates the number of psyllids captured per block and recommend sprays based on four different thersholds,and to determine the regions with the highest risk within the states of São Paulo, Brazil, and California, Florida, and Texas, USA. The above-mentioned risk was calculated based on an agrometeorological model for estimating the number of psyllids per block and the sprays recommended for its control, based on favorable weather conditions for estimated citrus sprouting, combined with the number of *D. citri* generations estimated by a degree-days model. For running the models, daily meteorological data of average air temperature, relative humidity, wind speed, and rainfall, on a spatial scale of 50 by 50 kilometers, were used for all assessed states for the period between 1981 and 2015. After calculating the number of recommended insecticide sprays based on the agrometeorological model for the four captures thresholds (trap captures of 1, 2, 3 or 4 psyllids per block, which were respectively classified as very conservative, conservative, medium and little conservative). For this, a multi-linear regression equations were then generated to spatialize the number of sprays per month and per year, determining the risks in all states, based on the latitude, longitude and altitude as independent data. The risks were classified into five risk classes (very low, low, medium, high and very high) for both time scales. The next step was to generate air temperature maps, also based on multi-linear regression equations having latitude, longitude and altitude as parameters, which were used to spacialize the number of psyllid generations per month and year, according to the degree-days required to complete its life cycle (thermal time of 211 °C days and base temperature of 13.5 °C). Finally, the risk maps based on the number of sprays were multiplied by the number of estimated generations in order to obtain the final risk of occurrence of the psyllid, which was classified in five risk classes for each 50 x 50 km grid in each state. All maps were validated using independent data. The estimated annual average risk for psyllid occurrence was greater in Florida than in the other assessed states, which presented risks in the following decreasing order: São Paulo; Texas; and California. In Florida, Texas and California, psyllid risk begins to rise in the spring, increasing further during the summer, and then declines to its lowest level in the winter, similar to what happens in the state of São Paulo. In the northern hemisphere, the risks fo psyllid occurrence is greater than in the southernparts of the states. In São Paulo the greatest risk is in the northern part of the state.

Keywords: Citrus, *Diaphorina citri*, *Candidatus* Liberibacter spp., Weather data, Interannual variability, Orchard planning, Control decision-making.

3.1. Introduction

The citrus crop is an important source of income for Brazil and the United States of America (USA), which together are responsible for a large part of world's orange production (FAOSTAT, 2021). However, the citriculture in these countries is facing several challenges, mainly related to phytosanitary problems. In recent years, a phytoplasma-incited disease named huanglongbing (HLB) has emerged as the most damaging disease of citrus worldwide (GRAÇA, 1991; COLETTA-FILHO et al., 2004; BRUCE et al., 2005), which has required the eradication of millions of trees from citrus orchards, increasing the production costs (BELASQUE JUNIOR et al., 2009).

In 2005, HLB was detected in orchards of Florida, USA (HALBERT, 2005), one year after the first documented occurrence of this disease in Brazil, in the State of São Paulo (COLETTA-FILHO et al., 2004). Since then, citrus production has decreased yearly (FAOSTAT, 2021), especially in Florida, which is the main citrus producing state in the USA (USDA, 2020).

HLB is a disease caused by specialized bacteria named *Candidatus* Liberibacter asiaticus, *Candidatus* Liberibacter americanus and *Candidatus* Liberibacter africanus (BOVÉ, 2006). The first one of them is the predominant HLB pathogen in the United Stated (MANJUNATH et al., 2008) and is also the most important HLB pathogen in Brazil (LOPES et al., 2009). Transmission of this disease occurs through a psyllid vector, *Diaphorina citri* (CAPOOR et al., 1967; GALLO; GALLO, 2002). Plants infected by the bacteria develop yellowish colored leaves, premature leaf fall, reduced branch size, fruit with yellowish spots and asymmetrical shape, deformed and sterile seed, and premature fruit drop. Moreover, trees become unproductive in few years, leading to their eradication from the orchards (BOVÉ, 2006; BOSCARIOL-CAMARGO et al., 2010).

The climatic conditions of the citrus regions in Brazil and USA favor both citrus production and HLB, which is closely linked to the occurrence of the sprouting process, when the psyllid finds more suitable conditions to attack the plants and transmit the bacteria. Sprouts can occur over a wide range of temperatures, from 12 to 31 °C, tolerating up to 37 °C (Reuther, 1973). The optimum temperature for sprouting is between 20 and 30 °C (KRIEDEMANN, 1971; DAVIES; ALBRIGO, 1994; RIBEIRO et al., 2012). Soil water availability can change citrus phenology, since plants´ sprouting is often triggered by intense water deficiency followed by rainfalls of at least 20 mm. Sprouting in citrus orchards promotes the growth of the vector population, since it favors psyllid oviposition (PARRA et al., 2010), since young insects prefer new branches, whereas adults, although preferring the new branches, also attack the older ones (DINIZ, 2013).

The control of the vector should consider the two ways of insect dispersal, which are named primary and secondary (BERGAMIN FILHO et al., 2016). According to these authors, primary dispersal occurs from one property to another, whereas the secondary occurs within the property, through infection by the psyllid from one plant to another within a citrus grove. Primary dispersal depends on the control outside the property (regional), and if it does not occur there will be constant infections on the farm (local). Secondary dispersal is easier to control since it depends on local management, but less effective when the regional control does not happen.

As HLB is disperted by the psyllid and it prefers young tissues, being both regulated by weather conditions, it is of major importance to know which are their climatic requirements and, therefore, the conditions that favor HLB development, having as intention to improve the rational management as well as to identify the areas of highest risk for this disease, both at regional and local levels. Considering that, the hypotheses of the present study are that the risk of occurrence of HLB can be determined through the use of a calibrated and validated agrometeorological model for estimating psyllid captures and that this model can be applied in the citrus regions of Brazil and USA in order to assist growers to adoption more effective strategies to time insecticide sprays for controlling HLB. Based on these two hypothesis, the objectives of this study were: to determine the climatic risk of Asian psyllid citrus occurrence in the main citrus producing regions of Brazil and USA, at annual and monthly basis; and to determine the regions with the highest risk of HLB within the states of São Paulo, Brazil, and California, Florida, and Texas, USA.

3.2. Material and Methods

The general scheme used for determining the risk of occurrence of Asian citrus psyllid, with subsequent control recommendations is presented in Figure 1. This flow chart shows all the procedures for calculating the number of psyllid generations, the number of psyllids captured per block, the recommended insecticide sprays, and the final map. These procedures were applied for the states of São Paulo, Brazil, and states of California, Florida and Texas, USA.

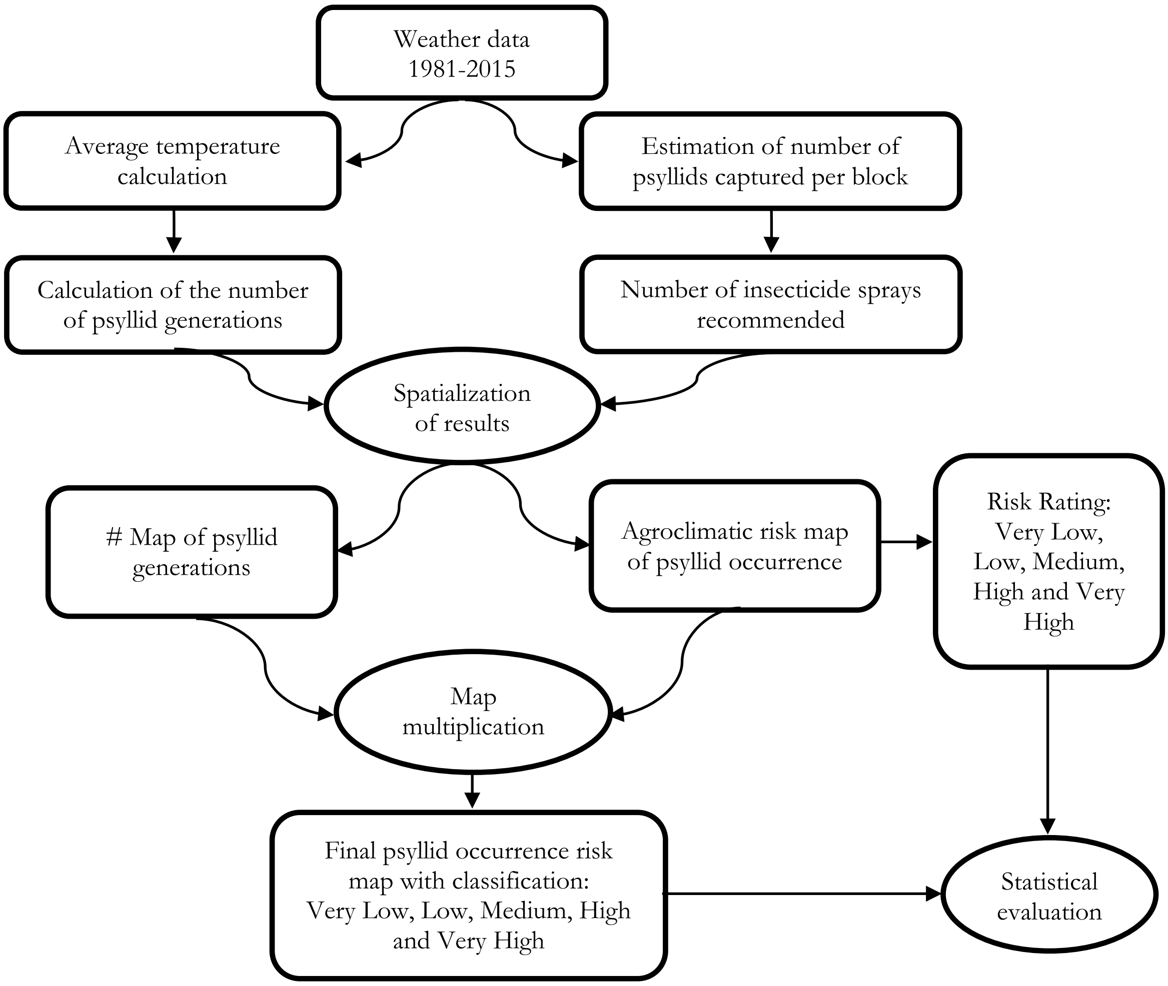

Figure 1. Scheme of determination of agroclimatic risk of Asian citrus psyllid occurrence in the main producing regions of Brazil and USA.

3.2.1. Weather data

Daily weather data (maximum, minimum and average temperature, relative humidity, wind speed, solar radiation, and rainfall) used to run the models for determining the risk of psyllid occurrence in orange orchards in the states of São Paulo, Brazil, and California, Florida and Texas, USA, were obtained from public gridded databases as follows: state of São Paulo – gridded (50 x 50 km) database of Xavier et al. (2016), for the period between 1981 and 2015; states of California, Florida and Texas – gridded (50 x 50 km) database from the PRISM Climate Group, Oregon State University, except for wind speed data that were provided by the NASA/POWER gridded (50 x 50 km) database, both for the period from 1981 to 2015. All these data were submitted to a consistency analysis for filling in data gaps and fix possible errors.

3.2.2. Estimation of the number of psyllids captured per block and control recommendation

Psyllids attack citrus plants mainly when new sprouts are available and the insects are in their developmental phase (PARRA et al., 2010; DINIZ, 2013). For estimating the risk of psyllid occurrence, an agrometeorological model based on the water deficit greater or equal than 5 mm in 10 days, followed by rainfall greater or equal than 5 mm in the next 5 days and air temperature between 16 and 28 °C in at least 4 out next 7 days. After that, the number of days under the favorable conditions in the last 14 days is computed, which represents the independent variable in the model, named as X3 (Equation 1). This model was previously calibrated and validated for the states of São Paulo and Florida, presenting a high level of correct estimates when considered four different thresholds for psyllids captured per block, with the fraction of correct estimates greater than 90%. To obtain the daily water deficit, water balance was calculated according to the Thornthwaite and Mather (1955) method, with potential evapotranspiration calculated by the Penman-Monteith method (ALLEN et al., 1998) and for a soil water holding capacity of 100 mm.

$$\frac{Psyl.}{Bloc.} = 0.3312 * X3 + 1.7412 \qquad (1)$$

where: Psyl./Bloc. is the number of psyllids captured per block in interval of 7 days; and X3 = number of days in 14 days with water deficit ≥ 5mm in 10 days followed by rainfall ≥ 5mm in the next 5 days and air temperature between 16 and 28 °C in at least 4 out 7 days.

After calculating the number of psyllids captured per block using equation 1, four different psyllid-capture thresholds were used to recommend vector control. These thresholds, for a 7 day interval, were: 1 psyllid captured per block (Very conservative); 2 psyllids captured per block (Conservative); 3 psyllids captured per block (Medium); and 4 psyllids per block (Little conservative), and defined the recommendations of insecticide spray, considering an action period of 7 days. Finally, the number of sprays per month and year were computed, according to the model´s recommendations.

3.2.3. Number of psyllids generations

As the agrometeorological model estimates the risk of psyllid occurrence based only on the favorable weather conditions for estimated citrus sprout, the number of psyllids generations estimated to complete the risk model with an insect development component. The thermal time or degree-days approach was used for estimating the number of generations per year and per month, based on the thermal time required by the *D. citri* to complete its life cycle (211 °C day for a base temperature of 13.5 °C) (PARRA et al., 2010). The accumulation of degree-days for each day was calculated by the difference between average air temperature and base temperature and the number of psyllids generations (NPG) was given by the following equation:

$$NPG = \frac{(Tavg - 13.5) \times DP}{211} \tag{2}$$

where: Tavg is the daily average air temperature; DP is the number of day in the considered period [month (January, March, May, July, August, October and December – 31 days; February – 28 days; or April, June, September and November – 30 days) or year (365 days)]; 13.5 represents the psyllid base temperature, in °C, and 211 is the thermal time for the psyllids to complete their life cycle, in °C day, and start a new generation.

3.2.4. Asian psyllid risk of occurrence map

For determination of the risk for Asian psyllid occurrence in the main producing regions of Brazil and USA, the agrometeorological model, presented previously, was used to predict the psyllid captures per block, with subsequent calculation of the sprays recommended for control of the psyllid, according to the different thresholds considered and for the monthly and annual time scales. Besides that, the number of psyllid generations, also at monthly and annual time scales, was determined for each assessed location. The maps of these two variables were prepared and multiplied, defining the magnitude of the favorability for HLB vector occurrence. These maps were generated using ArcGIS 10.6.1 Software (ESRI). The spatialization of these two variables (number of psyllids captured per block and number of psyllid generations) was done through the multiple linear regression methods. This method uses the correlation of the dependent variables (captures and number of generations) with latitude, longitude and altitude, since both psyllid variables depend on the climatic conditions, which in turn depend on the geographic coordinates and elevation of the region. The general formats of these multiple linear models are presented below:

$$NSp = a + b * Lat + c * Long + d * Alt + e * Lat^2 + f * Long^2 + g * Alt^2 + h * Lat * Long + i * Lat * Alt + j * Long * Alt \tag{3}$$

where: NSp is the estimated number of insecticide sprays by the agrometeorological model; a is the linear coefficient of the equation; b, c, d, e, f, g, h, i and j are the angular coefficients of the regression equation; Lat is the latitude in decimal degrees; Long is the longitude in decimal degrees, and Alt is the altitude in meters.

$$NPG = a + b * Lat + c * Long + d * Alt \quad (4)$$

where: NPG is the number of psyllid generations; a is the linear coefficient of the equation; b, c, and d are the angular coefficients of the regression equation; Lat is the latitude in decimal degrees; Long is the longitude in decimal degrees, and Alt is the altitude in meters.

For making the maps from these two multiple linear regressions, latitude and longitude were transformed in raster files, whereas for altitude came from Shuttle Radar Topographic Mission (SRTM), developed by National Aeronautics and Space Administration (NASA) and National Geospatial Intelligence Agency (NGA) in USA. The SRTM imagens make available the Digital Elevation Model (DEM) for a resolution of 90 x 90 m, which allows to determine altitude at this resolution for the entire globe. Once spatialized, latitude, longitude and altitude were used to calculate NSp and NPG for each pixel of 90 x 90 m, resulting in spatial map of these variables.

Using equations 3 and 4, spatial maps of NSp and NPG and their multiplication were obtained and reclassified, as presented in Figure 2, obtaining the Asian psyllid occurrence risk map.

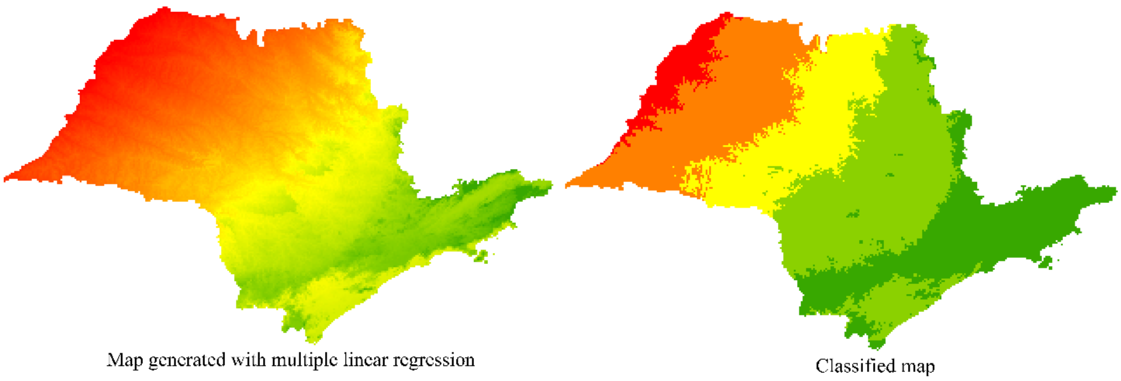

Figure 2. Examples of the maps generated with the proposed Asian psyllid risk of occurrence model, with the results from the multiple linear regression approach (left) and the final map after classification (right).

The Asian psyllid occurrence risk determination, climatic data from 1981 to 2015 were used. The psyllid favorability for every year was determined by the multiplication of NSp and NPG, as mentioned above, and then the monthly and annual data for all series were assessed to obtain a weighted risk, which considered the number of years in which each of the five favorability classes occurred for each location, as follows:

$$WRisk = \left(\frac{(VL*1+L*2+M*3+H*4+VH*5)-X}{Y-Z}\right)*100 \quad (6)$$

where: WRisk is the weighted risk for the entire weather series; VL, L, M, H, and VH represent, respectively. Very Low, Low, Medium, High and Very High classes of favorability, when considering the NSp alone or when using NSp and NPG together. In the numerator, X represents the 35 years of meteorological data used to calculate climate risk. In the denominator, Y represents if in the 35 years of data over the entire period the risk is very high (35 * 5 = 175) and Z if in the 35 years the risk would be very low (35 * 1 = 35).

Tables 1 and 2 show the ranges used for risks based on NSp and its combination with the NPG, for stablishing the classes of risk for the states of São Paulo, California, Florida and Texas, respectively for the monthly and annual time scales.

Table 1. Classes of climate-based risk levels of psyllid occurrence as a function of the number of recommended insecticide sprays (NSp) and its combination with the number of psyllid generations for the annual time scale.

Risk	Risk based on NSp	Risk based on NSp*NPG
Very Low (1)	≤15	≤384
Low (2)	15.01-40	384.01-768
Medium (3)	40.01-65	768.01-1152
High (4)	65.01-90	1152.01-1536
Very High (5)	>90	>1536

Table 2. Classes of climate-based risk levels of psyllid occurrence as a function of the number of recommended insecticide sprays (NSp) and its combination with the number of psyllid generations for the monthly time scale.

Risk	Risk based on NSp	Risk based on NSp*NPG
Very Low (1)	≤15	≤44
Low (2)	15.01-40	44.01-88
Medium (3)	40.01-65	88.01-132
High (4)	65.01-90	132.01-176
Very High (5)	>90	>176

3.2.5. Data analysis

To evaluate the accuracy of the climate-based risk of psyllid occurrence maps, 70% of the data (locations) were used for making the maps and the other 30% were used for maps validation. For evaluation, the calculated risks for the climatic series obtained with the previously presented models were compared to the information obtained from the maps, using the two approaches, NSp and NSp*NGP. The following statistical indices were used: correlation coefficient (*r*); Willmott agreement index (*d*); and confidence index (*c*) (CAMARGO; SENTELHAS, 1997), in addition to Mean Error (ME), Mean Absolute Error (MAE), Absolute Mean Percentage Error (AMPE) and Fraction of Correct Estimates (Fc).

3.3. Results

3.3.1. Inter-annual variability of Asian psyllid occurrence risk

Figure 3 shows the inter-annual variation of the psyllid occurrence risk, considering the control levels of 1 and 2 psyllids per block, in the different regions of the state of São Paulo. These data show that the risk for the thresholds of 1 and 2 psyllids per block varies from low (2) to very high (5), which the majority of the years with high (4) risk, mainly in the central, northwest and eastern regions of the state. Considering only the last five years (from 2011 to 2015), the risk was higher in the center, east and northwest regions of the state, and lower in the south and north, whereas in the west the risk varied between medium (3) and high (4).

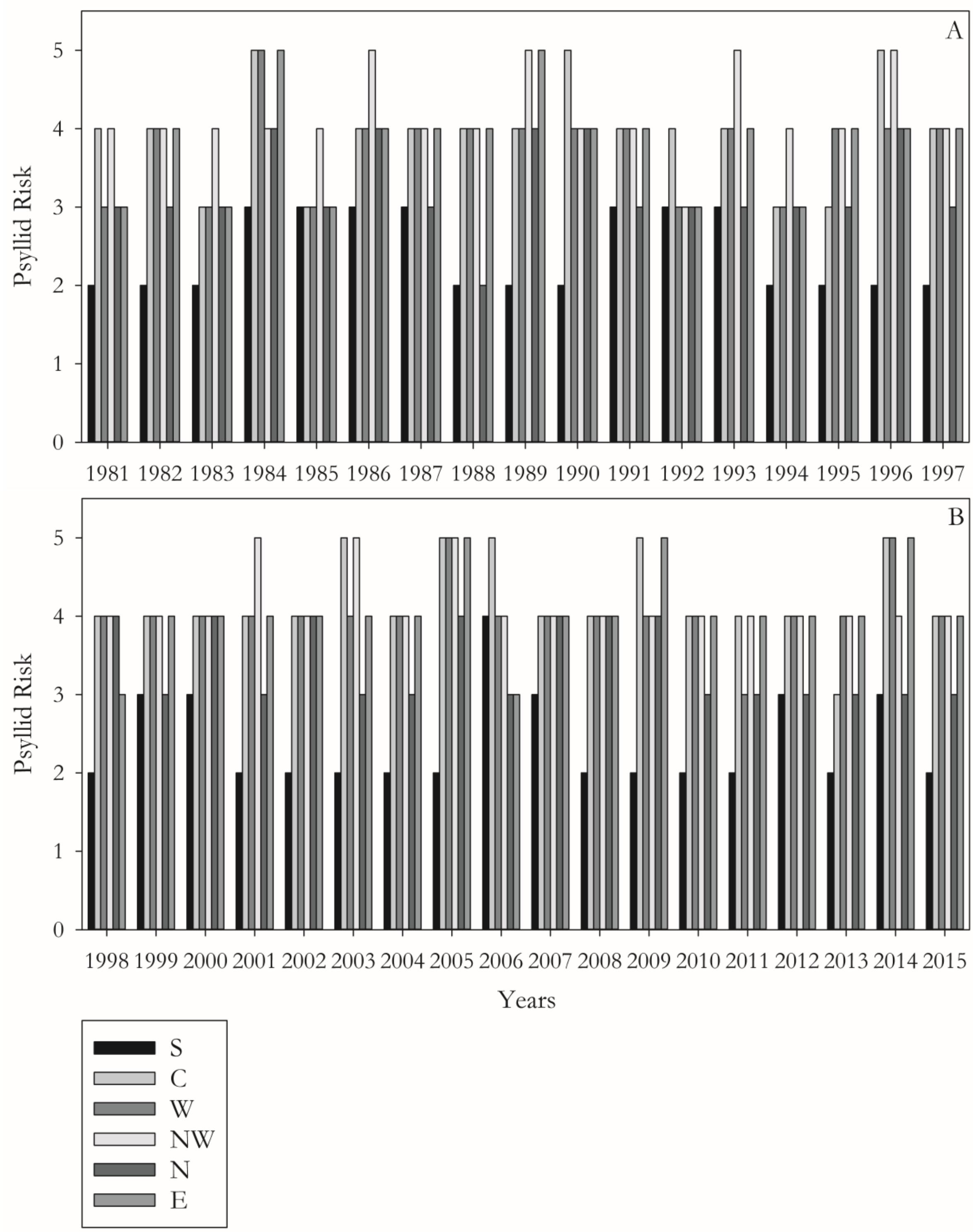

Figure 3. Inter-annual variation of the Asian psyllids occurrence risk for the thresholds of 1 and 2 psyllids per block in the state of São Paulo, Brazil, considering its different regions [South (S), Center (C), West (W), Northwest (NW), North (N), and East (E)] and the periods between 1981 and 1997 (A) and between 1998 and 2015 (B).

In the state of Florida (Figure 4), the psyllid occurrence risk ranged between high (4) and very high (5) in all years and in the south, center, east and west regions of the state, whereas in the north and northwest regions no risk was observed (data not shown). Similar results were obtained for the states of Texas (Figure 5) and California (Figure 6); however, with lower risks for these two states. In Texas, the psyllid occurrence risk ranged between low (2) and very high (4), whereas in California such risk varied between very low (1) and medium (3).

Analyzing all the locations together, one can see that California is the state with the lowest risk for psyllid occurrence in citrus orchards, whereas the state of Florida is the one with the highest risk. Texas and São Paulo have similar and an intermediate risk. These risks are basically controlled by weather conditions that favor new citrus sprouting (water deficit followed rainfall and suitable temperature) and psyllid development (temperature or degree-days).

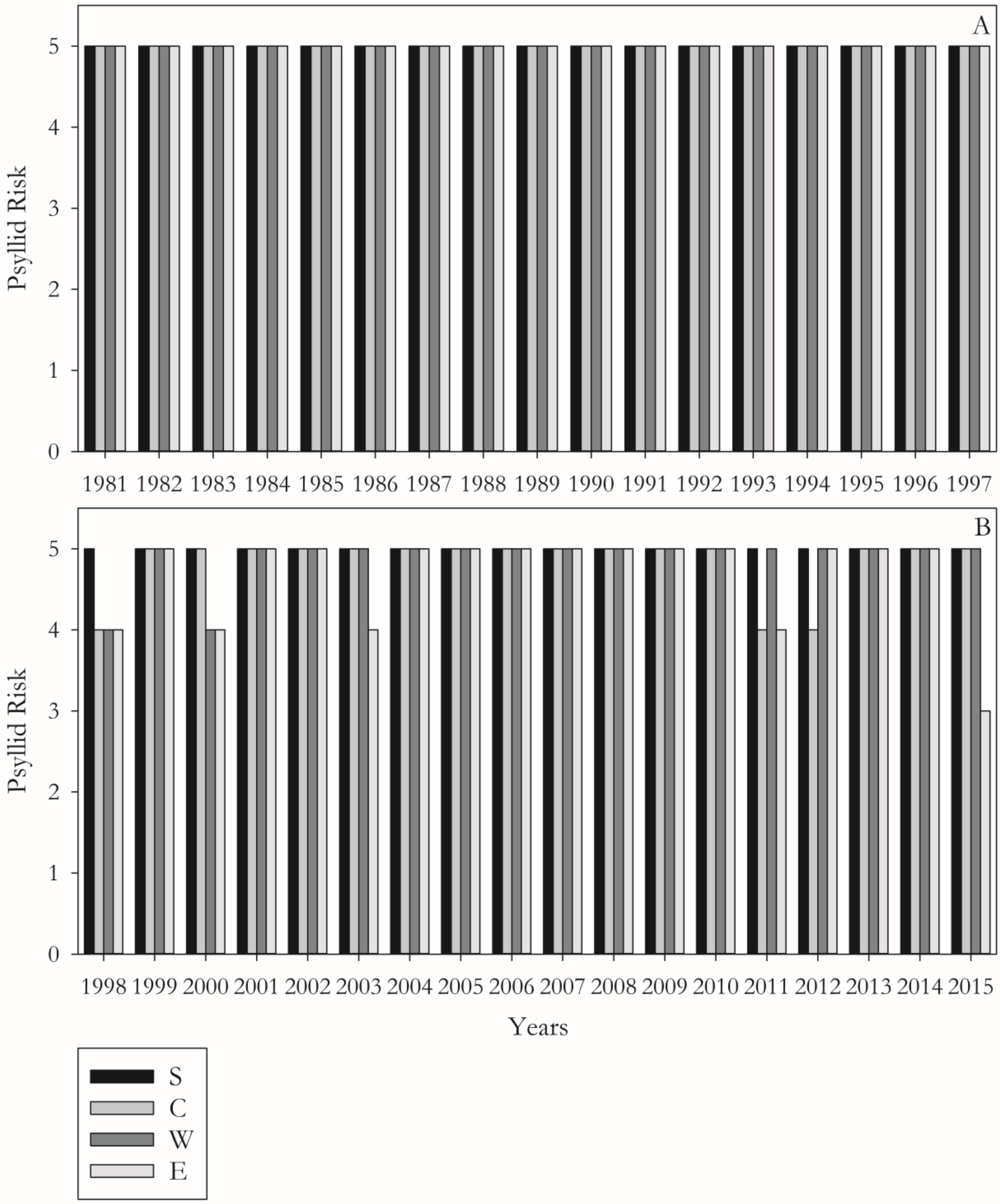

Figure 4. Inter-annual variation of the Asian psyllids occurrence risk for the thresholds of 1 and 2 psyllids per block in the state of Florida, USA, considering its different regions [South (S), Center (C), West (W) and East (E)] and the periods between 1981 and 1997 (A) and between 1998 and 2015 (B).

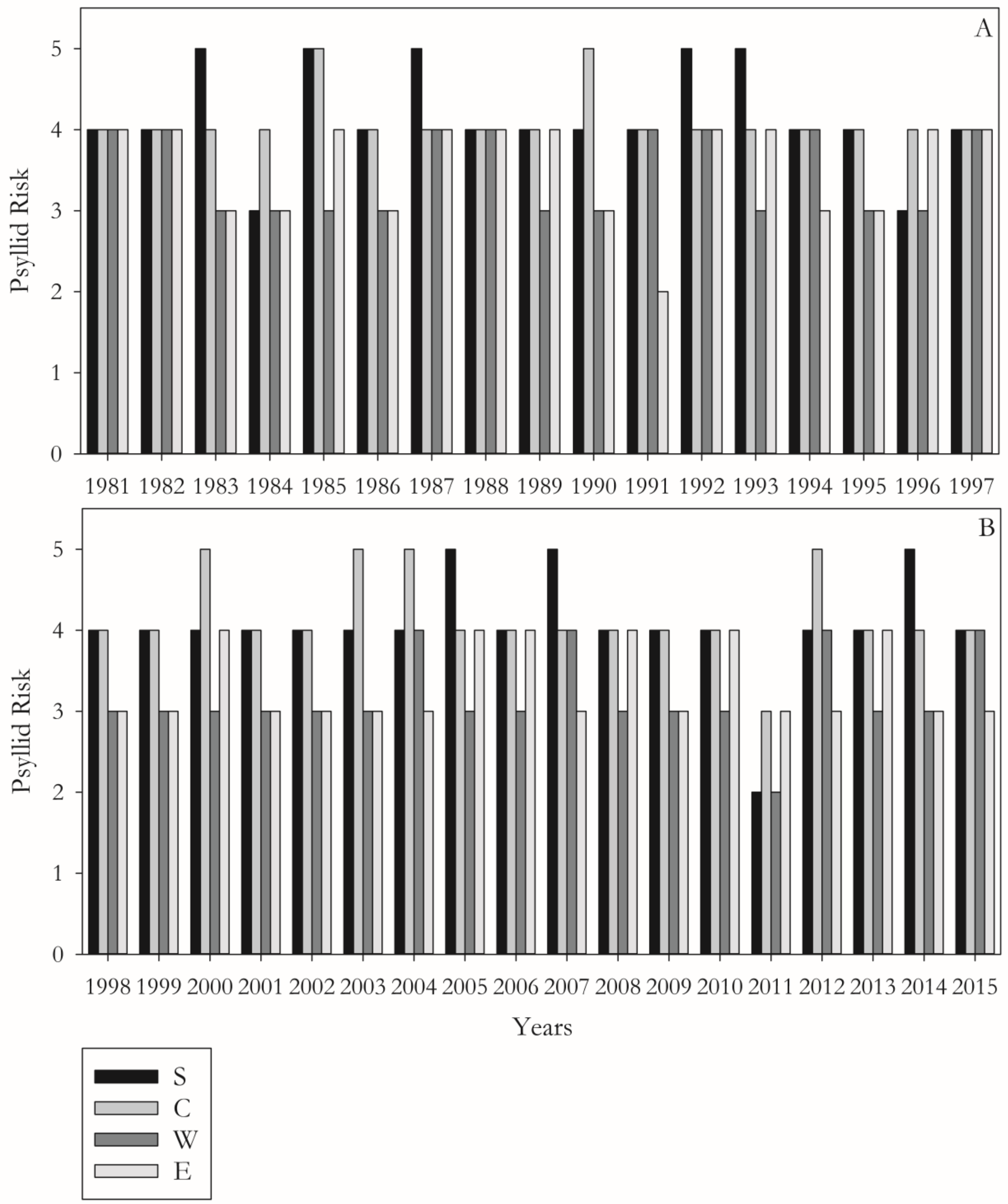

Figure 5. Inter-annual variation of the Asian psyllids occurrence risk for the thresholds of 1 and 2 psyllids per block in the state of Texas, USA, considering its different regions [South (S), Center (C), West (W) and East (E)] and the periods between 1981 and 1997 (A) and between 1998 and 2015 (B).

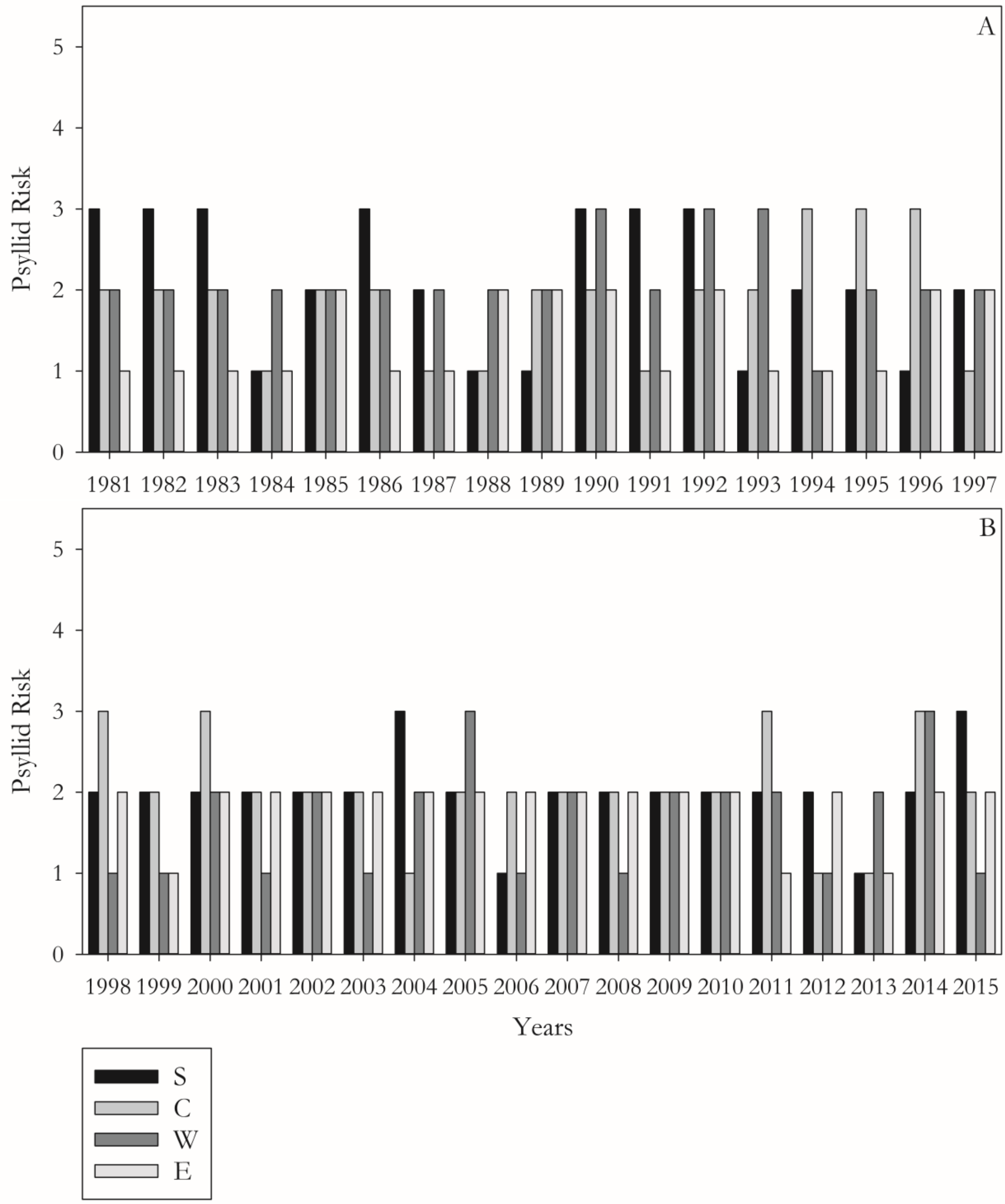

Figure 6. Inter-annual variation of the Asian psyllids occurrence risk for the thresholds of 1 and 2 psyllids per block in the state of California, USA, considering its different regions [South (S), Center (C), West (W) and East (E)] and the periods between 1981 and 1997 (A) and between 1998 and 2015 (B).

3.3.2. Average annual Asian psyllid occurrence risk

Figures 7, 8, 9 and 10 present the average annual risk for psyllid occurrence in the assessed states, considering the risk associated to the availability of estimated citrus sprouts and its combination with the number of psyllid generations, calculated by degree-days, for the thresholds of 1 and 2 psyllids per block and of 3 and 4 psyllids per block, respectively for the states of São Paulo, Florida, Texas, and California. The risk associated to the thresholds of 1 and 2 or 3 and 4 psyllids captured per block per week were very similar for all the assessed states, as can be seen in the risk maps generated for each state. The coefficients of the multiple linear regressions used for spatialization of the risks for all the states under study are presented in the Appendices A1 to A4. The psyllid occurrence risk calculated only with the favorable climatic conditions for estimated citrus sprouting is in the Appendices B1 to B4.

Table 3 shows the statistical analysis of the average annual risk maps for the two captures thresholds, as well as for mean daily temperature map that was used for the calculation number of psyllids generation. Considering the threshold of 1 and 2 psyllids per block comparing the calibration with the validation, it has a better performance than the threshold of 3 and 4 psyllids per block, with higher *r*, *d*, *c*, and % of hits in the calibration phase. The performance of the temperature map was also very good, with high precision ($r \geq 0.91$) and accuracy ($d \geq 0.95$), and general errors (MAPE) of only 2%.

Table 3. Statistical analysis of the average annual Asian psyllid occurrence risk (R) maps for the thresholds of 1 and 2 psyllids per block and 3 and 4 psyllids per block, as well as for the average temperature map, used to calculate the number of psyllids generations with degree-days approach, considering the correlation coefficient (*r*), Willmott agreement index (*d*), confidence index (*c*), mean error (ME), mean absolute error (MAE), mean absolute percentage error (MAPE) and percentage of hits [Hit (%)], during the calibration (Cal.) and validation (Val.) phases of the maps for the state of São Paulo, Brazil.

Threshold	*r*		*d*		*c*		ME (R)		MAE (R)		Hit (%)	
	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.
1 or 2 psyllids	0.81	0.67	089	0.80	0.71	0.54	-0.04	-0.07	0.16	0.21	84	79
3 or 4 psyllids	0.80	0.68	0.89	0.82	0.71	0.55	0	0	0.18	0.21	82	79
	r		***d***		***c***		**ME (°C)**		**MAE (°C)**		**MAPE (°C)**	
Temperature	0.93	0.91	0.97	0.95	0.90	0.87	0	-0.09	0.49	0.42	0.02	0.02

For the State of São Paulo, the threshold of 1 and 2 psyllids per block presented a greater risk compared to the threshold of 3 and 4 psyllids per block (Figure 7). Considering the threshold of 1 and 2 psyllids per block, the risk was very high in the west, high in the north, center and part of the west, medium in part of the center and north, medium in the south and east and low from south to east, close to the Atlantic Ocean. For the threshold of 3 or 4 psyllids per block, the risk map changed little, mainly for the zone with very high risk, which only occurred in a small part of the western region.

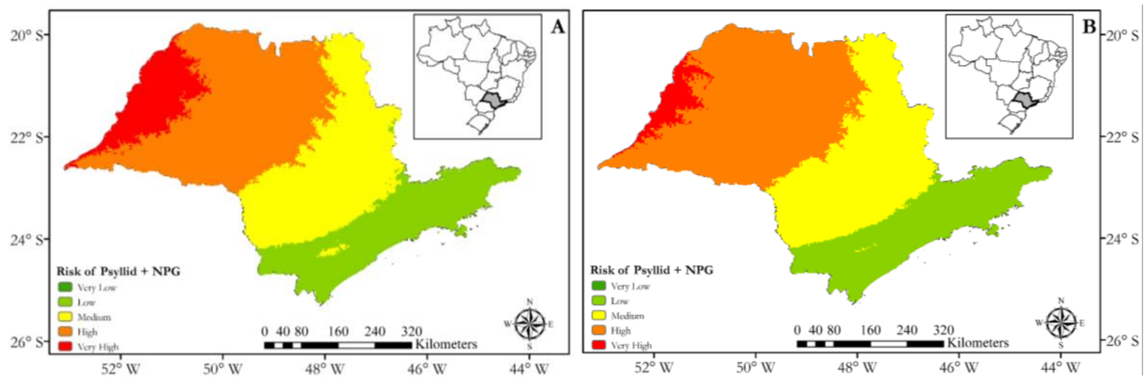

Figure 7. Average annual Asian psyllid occurrence risk in the state of São Paulo, Brazil, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the thresholds of 1 and 2 psyllids per block (A) and 3 and 4 psyllids per block (B).

For the state of Florida, the performance of the models to generate the risk maps was very high for both thresholds, during the calibration and validation phases, with *r*, *d* and *c* always above 0.64 and percentage of hits above 84% (Table 4). The performance of the temperature map was also very good, with high precision ($r \geq 0.98$) and accuracy ($d = 0.99$), and general errors (MAPE) of only 1%.

Table 4. Statistical analysis of the average annual Asian psyllid occurrence risk (R) maps for the thresholds of 1 and 2 psyllids per block and 3 and 4 psyllids per block, as well as for the average temperature map, used to calculate the number of psyllids generations with degree-days approach, considering the correlation coefficient (*r*), Willmott agreement index (*d*), confidence index (*c*), mean error (ME), mean absolute error (MAE), mean absolute percentage error (MAPE) and percentage of hits [Hit (%)], during the calibration (Cal.) and validation (Val.) phases of the maps for the state of Florida, USA.

Threshold	*r*		*d*		*c*		ME (R)		MAE (R)		Hit (%)	
	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.
1 or 2 psyllids	0.75	0.74	087	0.86	0.65	0.64	0.02	-0.05	0.15	0.16	85	84
3 or 4 psyllids	0.79	0.93	0.89	0.95	0.70	0.89	0	0.05	0.13	0.05	87	95
	r		***d***		***c***		**ME (°C)**		**MAE (°C)**		**MAPE**	
Temperature	0.98	0.99	0.99	0.99	0.98	0.98	0	0.05	0.23	0.23	0.01	0.01

The average annual risk for psyllids occurrence maps for Florida were very similar for the two assessed thresholds, with the main difference in the north of the state were the areas with low risk is larger for the threshold of 1 and 2 psyllids per block (Figure 8). For both thresholds, the risk was higher in the southernmost part of the state and decreased gradually toward the north. For the most traditional citrus regions of Florida the risk for psyllids occurrence ranged between high and very high.

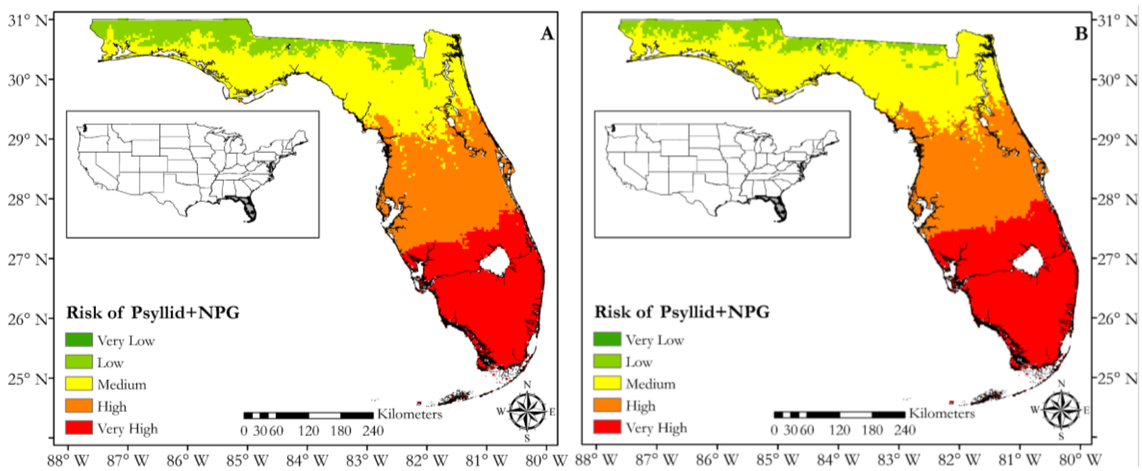

Figure 8. Average annual Asian psyllid occurrence risk in the state of Florida, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the thresholds of 1 and 2 psyllids per block (A) and 3 and 4 psyllids per block (B).

For the state of Texas, the performance of the models used to generate the risk maps were a bit worse than for the states of São Paulo and Florida, mainly for precision index (Table 5). Probably, the main reason for that is the fact that the psyllid capture model was developed for the two former states. Even considering the lower precision, the psyllid occurrence risk maps had the percentage of hits higher than 87% in all cases. Again, the performance of both maps was very similar, allowing the use of any of them for determining risks for psyllid occurrence. Errors (ME and MAE) were a bit higher for the threshold of 3 and 4 psyllids per block. The performance of the temperature map was also very good, with high precision ($r \geq 0.97$) and accuracy ($d = 0.99$), and general errors (MAPE) of only 2%.

Table 5. Statistical analysis of the average annual Asian psyllid occurrence risk (R) maps for the thresholds of 1 and 2 psyllids per block and 3 and 4 psyllids per block, as well as for the average temperature map, used to calculate the number of psyllids generations with degree-days approach, considering the correlation coefficient (*r*), Willmott agreement index (*d*), confidence index (*c*), mean error (ME), mean absolute error (MAE), mean absolute percentage error (MAPE) and percentage of hits [Hit (%)], during the calibration (Cal.) and validation (Val.) phases of the maps for the state of Texas, USA.

Threshold	*r*		*d*		*c*		ME (R)		MAE (R)		Hit (%)	
	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.
1 or 2 psyllids	0.59	0.52	0.77	0.72	0.45	0.38	0.03	0	0.29	0.15	89	87
3 or 4 psyllids	0.73	0.62	0.86	0.79	0.62	0.49	0	0.03	0.24	0.15	91	87
	r		*d*		*c*		ME (°C)		MAE (°C)		MAPE	
Temperature	0.97	0.99	0.99	0.99	0.96	0.98	0	-0.05	0.33	0.32	0.02	0.02

The risk maps for psyllid occurrence in Texas (Figure 9) were similar for the two thresholds assessed, with both ranging from very low in the northwestern too high in the south of the state. For the threshold of 1 and 2 psyllids per block, the risk of psyllid occurrence was very high only in a small area in the extreme south of the state. For the threshold of 3 and 4 psyllids per block, such area with high risk was not observed. For both thresholds, very low and low risks predominate in the state.

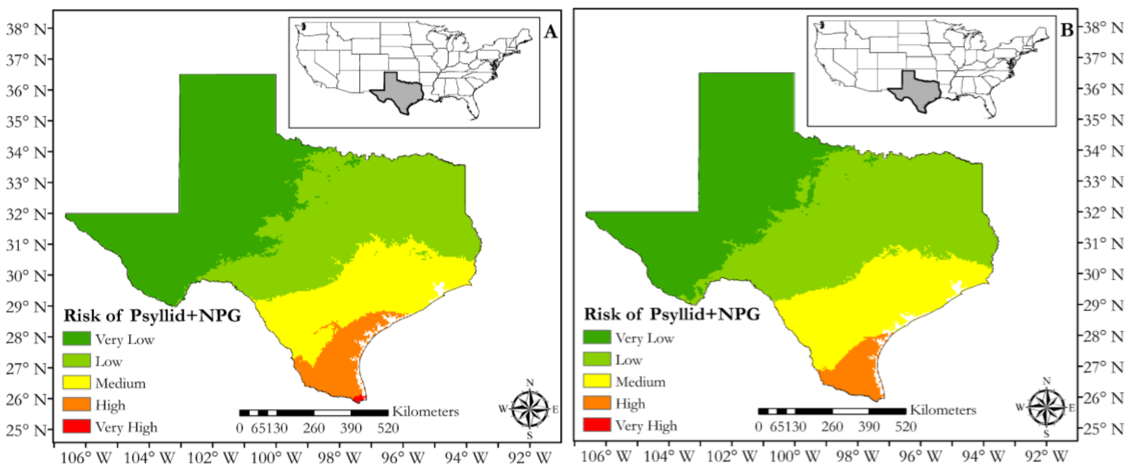

Figure 9. Average annual Asian psyllid occurrence risk in the state of Texas, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the thresholds of 1 and 2 psyllids per block (A) and 3 and 4 psyllids per block (B).

Table 6 presents the statistical performance of the psyllid occurrence risk maps for the two thresholds evaluated in this study for California. At the most conservative threshold (1 and 2 psyllids per block), the correlation, accuracy and general performance of the maps exceeded those of the less conservative threshold (3 and 4 psyllids per block), with both evaluations performing better in calibration than validation. California had the worst performance of the maps among the assessed states; however, the errors (ME and MAE) were relatively low and the percentage of correct hits was relatively high, between 91 and 92% in the calibration, and more that 89% in the validation. For temperature map, on the other hand, the performance was like the other evaluated states, however presenting errors of higher magnitude for the models of temperature, between 11 a 18%.

Table 6. Statistical analysis of the average annual Asian psyllid occurrence risk (R) maps for the thresholds of 1 and 2 psyllids per block and 3 and 4 psyllids per block, as well as for the average temperature map, used to calculate the number of psyllids generations with degree-days approach, considering the correlation coefficient (*r*), Willmott agreement index (*d*), confidence index (*c*), mean error (ME), mean absolute error (MAE), mean absolute percentage error (MAPE) and percentage of hits [Hit (%)], during the calibration (Cal.) and validation (Val.) phases of the maps for the state of California, USA.

Threshold	*r*		*d*		*c*		ME (R)		MAE (R)		Hit (%)	
	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.
1 or 2 psyllids	0.64	0.19	0.74	031	0.48	0.06	0.12	-0.06	0.15	0.15	91	88
3 or 4 psyllids	0.60	0.29	0.73	0.40	0.44	0.12	0.10	0	0.13	0.08	92	94
	r		*d*		*c*		ME (°C)		MAE (°C)		MAPE	
Temperature	0.95	0.93	0.97	0.97	0.93	0.91	0	0.29	1.13	1.24	0.11	0.18

In relation to the risks for psyllid occurrence in California, they are predominantly very low, with very small areas of low risk in the extreme south of the state, mainly for the threshold of 1 and 2 psyllids per block (Figure 10).

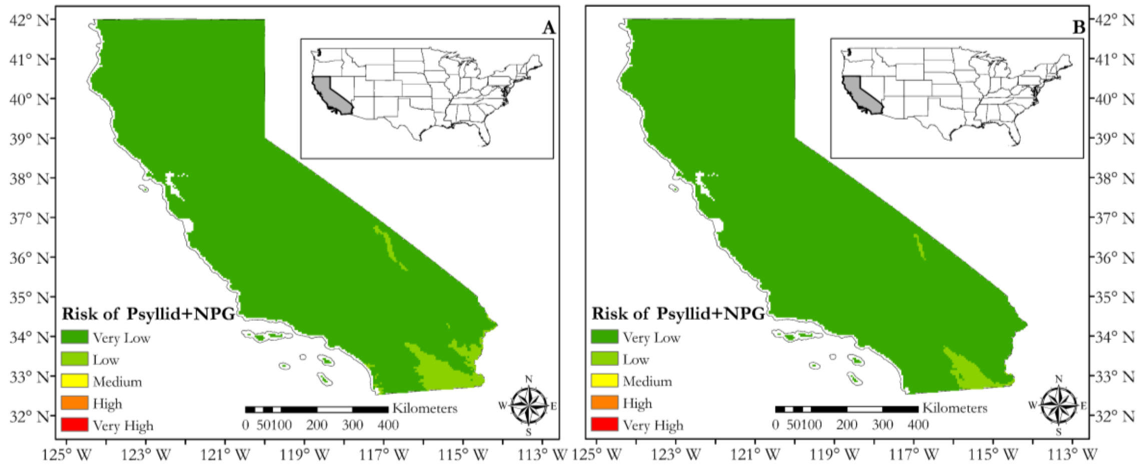

Figure 10. Average annual Asian psyllid occurrence risk in the state of California, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the thresholds of 1 and 2 psyllids per block (A) and 3 and 4 psyllids per block (B).

3.3.3. Average monthly Asian psyllid occurrence risk

The average monthly psyllid occurrence risks are shown in the Figures 11 to 18. All these maps are based on the average of the total monthly risk conditions from 1981 to 2015 for the four assessed states. In all of them the risks vary from month to month, and differences among them are observed, especially when comparing the state of São Paulo, in the southern hemisphere, with the USA states in the northern hemisphere. Thresholds of 1 and 2 psyllids per block and of 3 and 4 psyllids per block were grouped, as they presented the same NSp in the same month. The coefficients of the multiple linear models used to spatialize the average monthly climate risk for psyllid occurrence and the temperature for calculating the number of psyllids generations are presented in Appendix C1 to C4, whereas the maps with the climatic risk for psyllid occurrence on a monthly basis, estimated with the agrometeorological model for citrus sprouting, are in Appendix D1 to D8.

Table 7 presents the statistical parameters used in the evaluation of the multiple linear models used to spatialize the psyllid occurrence risk for the different thresholds and to estimate temperature for each month in the state of São Paulo. Over the months, the statistical parameters for the thresholds 1 and 2 psyllids per block and 3 and 4 psyllids per block are similar, with the month of September having the lowest correlation, accuracy, and performance, in both calibration and validation phases. ME and MAE varied over the months, with higher values observed in the validation when compared to the calibration. For the correctness of the models, the percentage of hits also was variable throughout the year, with the months of April and May (65%) having the lowest accuracy in the calibration and July (59%) in the validation for the threshold of 1 and 2 psyllid per block. When the threshold of 3 and 4 psyllids per block was considered, the percentage of hits also varied and was lower in the month of January (66%) in the calibration and March (66%) in the validation. Regarding temperature models, they presented high correlations, accuracies and performances, and errors of small magnitude. The performance of the multiple linear models used to create the maps can be considered as good, making it possible to spatialize the risks of psyllid occurrence in the state of São Paulo in a monthly basis.

Table 7. Statistical analysis of the average monthly Asian psyllid occurrence risk (R) maps for the thresholds of 1 and 2 psyllids per block and 3 and 4 psyllids per block, as well as for the average temperature maps, used to calculate the number of psyllids generations with degree-days approach, considering the correlation coefficient (*r*), Willmott agreement index (*d*), confidence index (*c*), mean error (ME), mean absolute error (MAE), mean absolute percentage error (MAPE) and percentage of hits [Hit (%)], during the calibration (Cal.) and validation (Val.) phases of the maps for the state of São Paulo, Brazil.

Thresholds	Months	*r*		*d*		*c*		ME (R)		MAE (R)		Hit (%)	
		Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.
1 or 2 psyllids	Jan	0.79	0.70	0.88	0.82	0.70	0.57	-0.06	0.03	0.32	0.31	68	69
	Feb	0.69	0.62	0.81	0.72	0.56	0.45	-0.06	0.24	0.21	0.31	79	72
	Mar	0.71	0.42	0.83	0.65	0.58	0.27	-0.07	0.03	0.22	0.38	78	66
	Apr	0.71	0.73	0.83	0.85	0.59	0.62	0	-0.07	0.35	0.28	65	72
	May	0.77	0.84	0.87	0.91	0.67	0.76	-0.13	-0.03	0.37	0.17	65	83
	Jun	0.88	0.73	0.94	0.80	0.82	0.59	0.01	0.10	0.16	0.31	84	72
	Jul	0.83	0.60	0.91	0.75	0.75	0.45	0.01	-0.10	0.22	0.45	78	59
	Agu	0.80	0.77	0.90	0.80	0.72	0.61	0.01	0	0.13	0.21	87	83
	Sep	0.29	0	0.49	0.30	0.14	0	0.18	0.17	0.24	0.17	76	86
	Oct	0.66	0.30	0.80	0.48	0.53	0.15	0.01	-0.10	0.13	0.31	87	69
	Nov	0.67	0.61	0.80	0.77	0.54	0.47	0.03	-0.03	0.29	0.24	71	76
	Dec	0.78	0.72	0.87	0.82	0.68	0.59	-0.09	-0.21	0.29	0.34	71	66
3 or 4 psyllids	Jan	0.75	0.76	0.86	0.85	0.65	0.65	-0.01	-0.07	0.34	0.28	66	72
	Feb	0.64	0.65	0.76	0.74	0.48	0.48	-0.09	0.21	0.26	0.28	74	76
	Mar	0.71	0.44	0.82	0.66	0.58	0.29	-0.10	-0.03	0.22	0.38	78	66
	Apr	0.72	0.54	0.84	0.72	0.61	0.39	0	-0.03	0.29	0.31	71	72
	May	0.79	0.66	0.88	0.77	0.70	0.51	-0.04	0.07	0.31	0.28	69	76
	Jun	0.88	0.77	0.94	0.84	0.82	0.65	0.01	0	0.16	0.21	84	83
	Jul	0.79	0.75	0.88	0.84	0.70	0.63	0	-0.03	0.24	0.24	76	79
	Agu	0.75	0.72	0.85	0.78	0.64	0.56	-0.03	0.03	0.24	0.24	76	79
	Sep	0.32	0	0.46	0.30	0.15	0.	0.18	0.17	0.21	0.17	79	86
	Oct	0.67	0.21	0.80	0.33	0.54	0.07	0.01	-0.07	0.07	0.28	93	72
	Nov	0.72	0.69	0.83	0.80	0.59	0.55	-0.01	-0.07	0.22	0.14	78	86
	Dec	0.76	0.54	0.86	0.71	0.65	0.38	-0.15	-0.10	0.29	0.24	71	76
		r		*d*		*c*		ME (°C)		MAE (°C)		MAPE	
Temperature	Jan	0.90	0.91	0.94	0.93	0.85	0.85	0	-0.15	0.49	0.41	0.02	0.02
	Feb	0.88	0.88	0.93	0.91	0.82	0.80	0	-0.13	0.51	0.41	0.02	0.02
	Mar	0.90	0.91	0.95	0.93	0.85	0.84	0	-0.13	0.51	0.41	0.02	0.02
	Apr	0.91	0.91	0.95	0.94	0.87	0.85	0	-0.13	0.55	0.43	0.03	0.02
	May	0.91	0.89	0.95	0.93	0.87	0.83	0	-0.13	0.56	0.45	0.03	0.03
	Jun	0.93	0.90	0.96	0.94	0.89	0.85	0	-0.10	0.56	0.46	0.03	0.03
	Jul	0.93	0.91	0.97	0.95	0.90	0.87	0	-0.08	0.56	0.48	0.03	0.03
	Agu	0.94	0.93	0.97	0.96	0.92	0.89	0	-0.06	0.57	0.49	0.03	0.03
	Sep	0.95	0.95	0.97	0.97	0.93	0.92	0	-0.07	0.54	0.44	0.03	0.02
	Oct	0.94	0.95	0.97	0.97	0.92	0.92	0	-0.08	0.54	0.43	0.03	0.02
	Nov	0.93	0.93	0.96	0.96	0.89	0.89	0	-0.11	0.52	0.41	0.02	0.02
	Dec	0.91	0.92	0.95	0.94	0.86	0.87	0	-0.14	0.52	0.41	0.02	0.02

The monthly risks for the thresholds of 1 and 2 psyllids per block are presented in Figure 11. The month of January (Figure 11A) presents four classes of risk, ranging from very low to high, increasing from the east to west. The highest risk is observed in the extreme west of the state, whereas the medium risk predominates in great part of the center-west of the state. In the other regions of São Paulo, the risk varies from low to very low. The risks in February (Figure 11B) and April (Figure 11D) are similar, varying from very low in the strip close to the Atlantic Ocean to medium in the center-west of the state. In March (Figure 11C), the risk decreases, with a small area with medium risk in the extreme west of the state, whereas in the other regions of the state the risk ranges between very low and low. Similar condition happens to the months of May (Figure 11E), June (Figure 11F), July (Figure 11G) and august (Figure 11H), when the risks never surpass the low level. From September (Figure 11I), the risk for psyllid occurrence increases again and remain increasing until December (Figures 11J, 11K and 11L), when the highest risks are observed in the state of São Paulo. Similar risk variability is observed for the threshold of 3 and 4 psyllids per block, however, with lower levels, as observed in Figure 12 for all months of the year.

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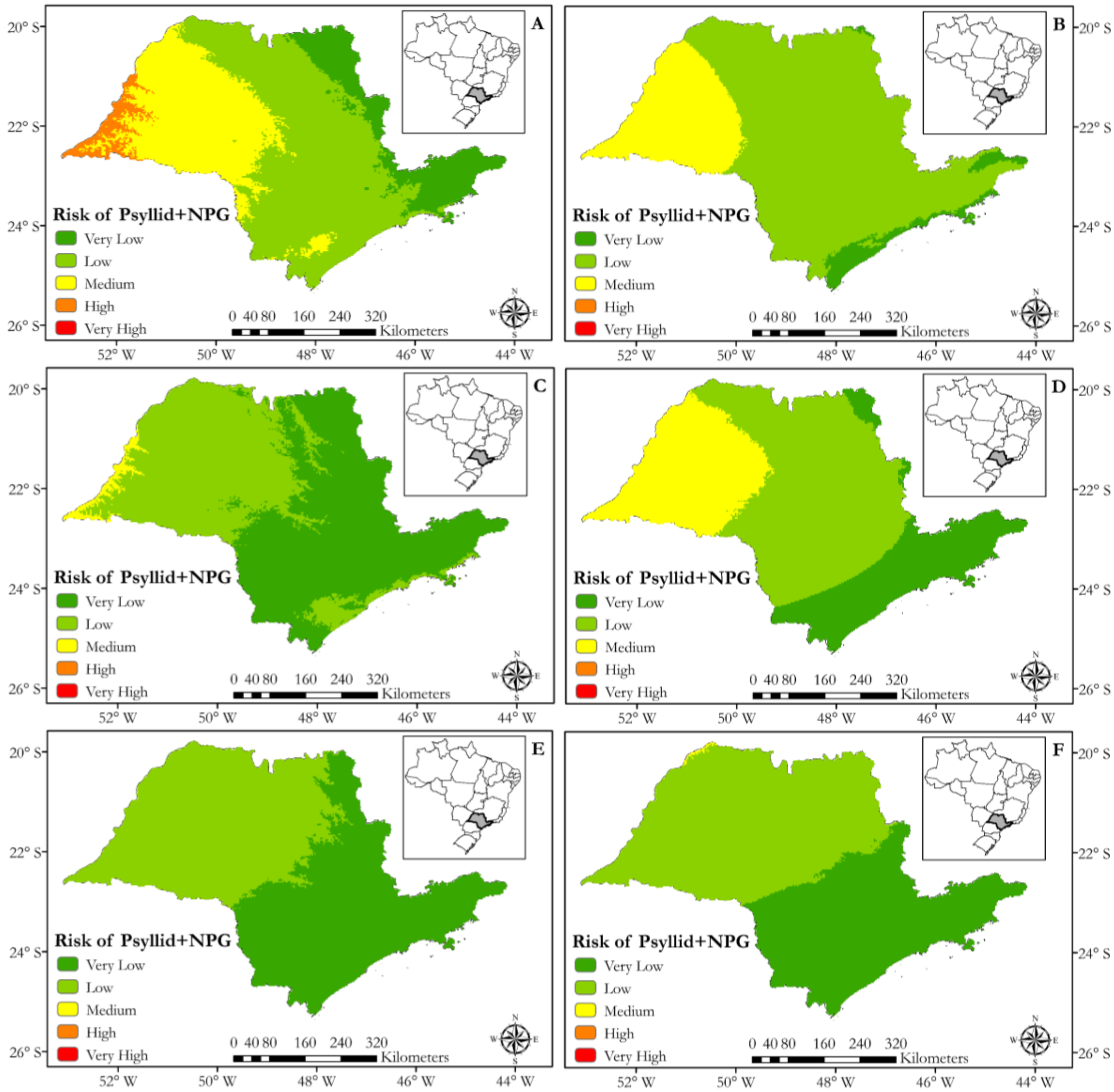

Figure 11. Average monthly Asian psyllid occurrence risk in the state of São Paulo, Brazil, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days , considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

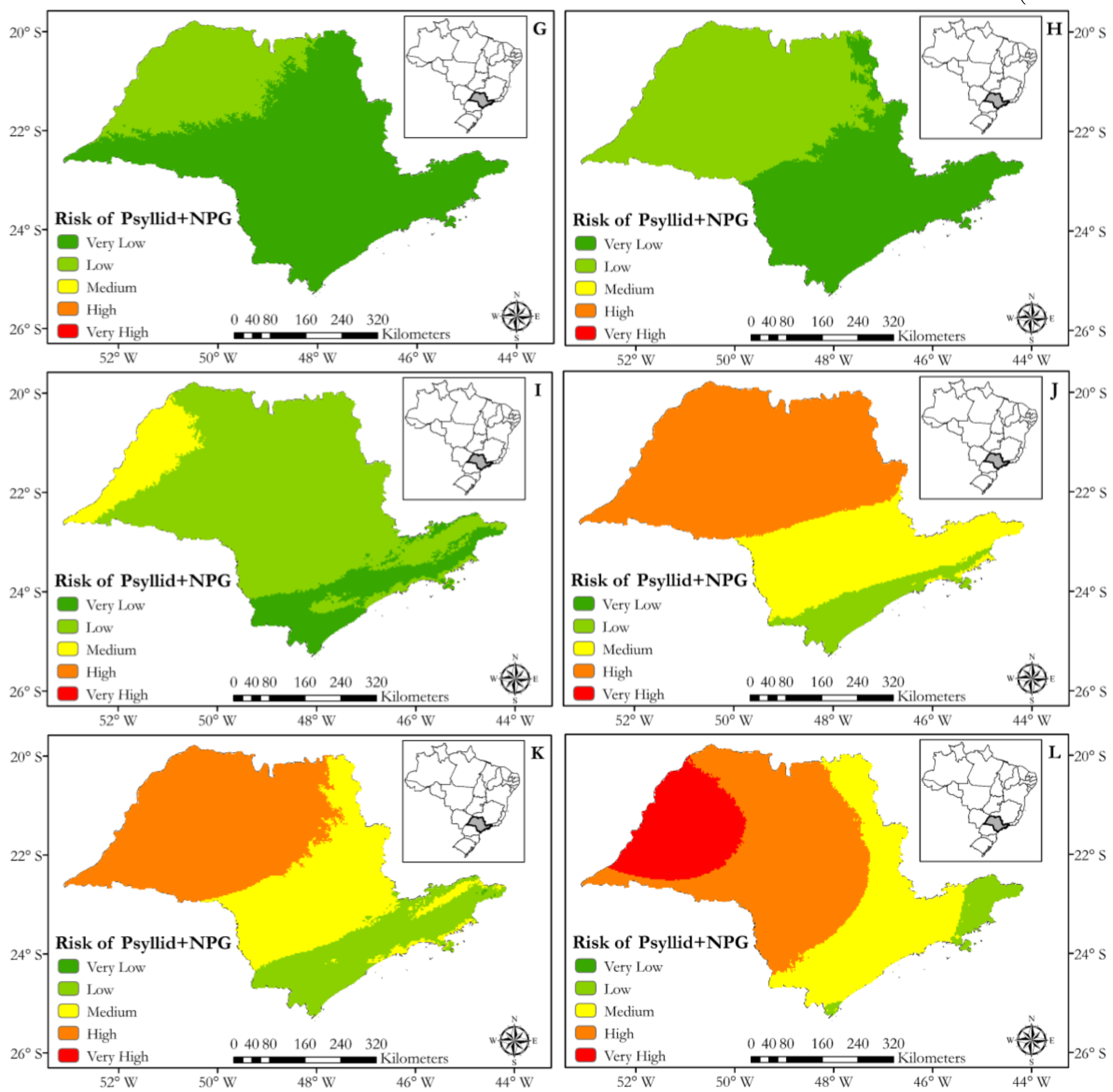

Figure 11. Average monthly Asian psyllid occurrence risk in the state of São Paulo, Brazil, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

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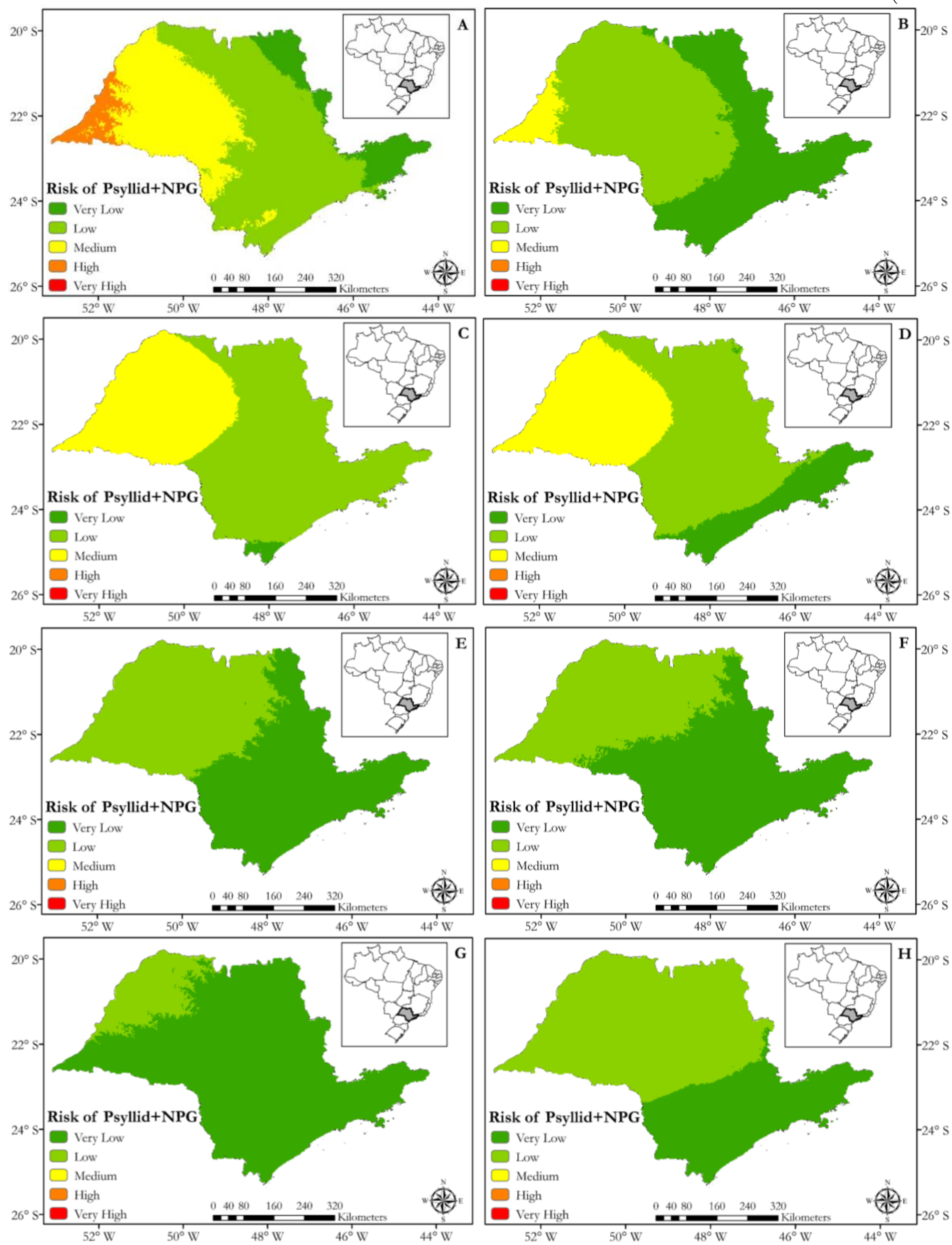

Figure 12. Average monthly Asian psyllid occurrence risk in the state of São Paulo, Brazil, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

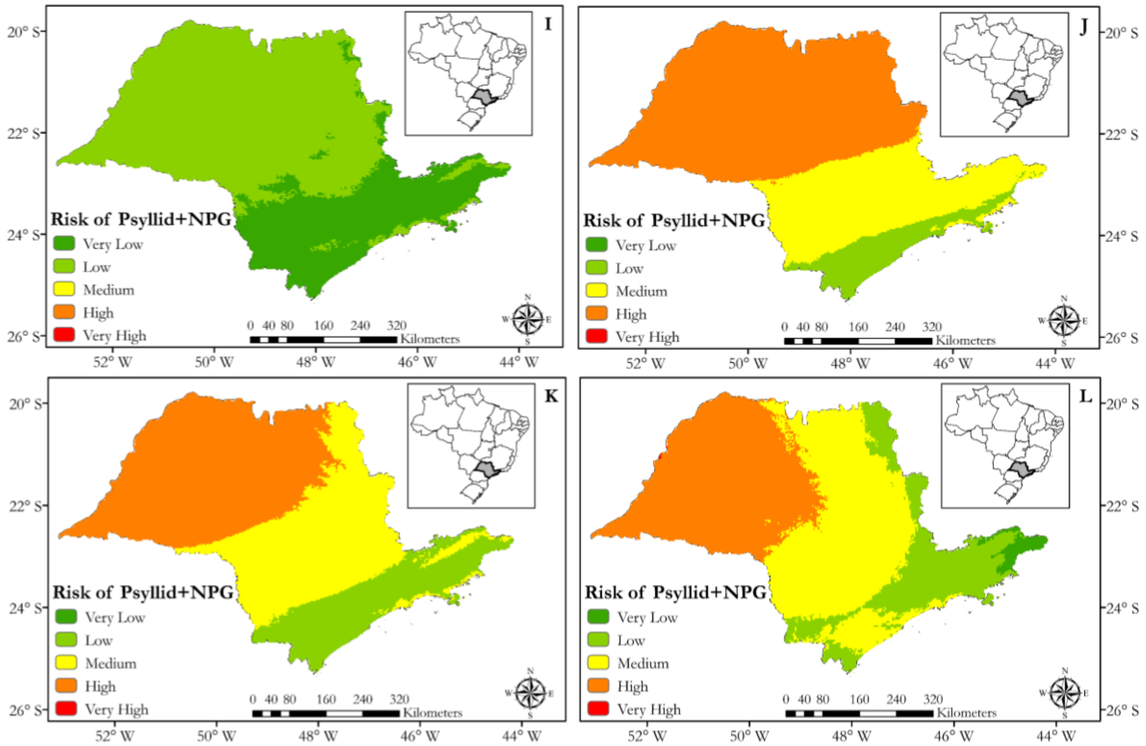

Figure 12. Average monthly Asian psyllid occurrence risk in the state of São Paulo, Brazil, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days , considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

Table 8 shows the statistical analyzes of the multiple linear models used for spatializations of the psyllid occurrence risks in a monthly basis as well as the model used to spatialize air temperature for the State of Florida, which was employed for determining the NPG. The models for spatialization of psyllid risks for both thresholds assessed (1 and 2 psyllids per block and 3 and 4 psyllids per block) showed the best performance from January to April, after when they decreased till June/August and increasing again just after that. Similar variation in the performance was observed for air temperature models. For both phases, calibration and validation, the multiple linear models used to spatialize risks presented the percentage of hits ranging between 58 and 95% for the threshold of 1 and 2 psyllids per block, whereas for the threshold of 3 and 4 psyllids per block this index varied between 47 and 98%. For the models used to spatialize air temperature and degree-days, the relative errors (MAPE) were of 2% in the maximum.

Table 8. Statistical analysis of the average monthly Asian psyllid occurrence risk (R) maps for the thresholds of 1 and 2 psyllids per block and 3 and 4 psyllids per block, as well as for the average temperature maps, used to calculate the number of psyllids generations with degree-days approach, considering the correlation coefficient (*r*), Willmott agreement index (*d*), confidence index (*c*), mean error (ME), mean absolute error (MAE), mean absolute percentage error (MAPE) and percentage of hits [Hit (%)], during the calibration (Cal.) and validation (Val.) phases of the maps for the state of Florida, USA.

Thresholds	Months	***r***		***d***		***c***		**ME (R)**		**MAE (R)**		**Hit (%)**	
		Cal.	**Val.**	**Cal.**	**Val.**	**Cal.**	**Val.**	**Cal.**	**Val.**	**Cal.**	**Val.**	**Cal.**	**Val.**
1 or 2 psyllids	**Jan**	0.94	0.96	0.97	0.97	0.91	0.93	-0.04	0.11	0.17	0.11	83	89
	Feb	0.95	0.97	0.97	0.98	0.92	0.95		0.11	0.17	0.11	83	89
	Mar	0.96	0.95	0.98	0.97	0.94	0.92	-0.04	-0.11	0.17	0.21	83	79
	Apr	0.84	0.80	0.91	0.88	0.76	0.71	-0.02	0.11	0.19	0.21	81	79
	May	0.63	0.69	0.79	0.79	0.50	0.54	-0.04	0.05	0.09	0.05	91	95
	Jun	0	0	0.34	0.35	0	0	-0.15	-0.16	0.15	0.16	85	84
	Jul	0.27	0.69	0.50	0.80	0.14	0.55	-0.06	-0.05	0.11	0.05	89	95
	Agu	0.32	0	0.48	0	0.16	0	-0.06	0.05	0.23	0.37	77	68
	Sep	0.54	0.47	0.75	0.69	0.41	0.32	0.04	0.05	0.21	0.37	79	63
	Oct	0.59	0.32	0.76	0.56	0.45	0.18	0.06	0.05	0.15	0.37	85	63
	Nov	0.51	0.58	0.71	0.76	0.36	0.44	0	0.05	0.21	0.26	79	74
	Dec	0.77	0.67	0.87	0.80	0.67	0.54	-0.02	-0.11	0.36	0.42	64	58
3 or 4 psyllids	**Jan**	0.92	0.93	0.96	0.96	0.88	0.89	-0.02	0.05	0.23	0.16	77	84
	Feb	0.94	0.97	0.97	0.98	0.91	0.95	-0.04	0.11	0.17	0.11	83	89
	Mar	0.95	0.93	0.97	0.96	0.92	0.90	0.02	-0.16	0.23	0.26	77	74
	Apr	0.79	0.81	0.88	0.86	0.70	0.70	-0.04	0.05	0.30	0.26	70	74
	May	0.95	0.28	0.97	0.59	0.92	0.16	0.02	0.05	0.02	0.26	98	74
	Jun	0.36	-0.12	0.58	0.33	0.21	-0.04	-0.21	-0.16	0.21	0.26	79	74
	Jul	0.44	0.48	0.69	0.71	0.30	0.34	-0.11	0.11	0.19	0.21	81	79
	Agu	0.59	0.49	0.75	0.62	0.45	0.31	-0.02	-0.05	0.11	0.26	89	74
	Sep	0.64	0.56	0.81	0.74	0.51	0.42	0.04	0	0.21	0.32	79	68
	Oct	0.61	0.48	0.74	0.62	0.45	0.29	-0.02	-0.05	0.15	0.26	85	74
	Nov	0.72	0.46	0.76	0.60	0.54	0.28	-0.02	0.21	0.11	0.21	89	79
	Dec	0.79	0.59	0.88	0.74	0.70	0.43	-0.02	-0.11	0.36	0.53	64	47
		r		***d***		***c***		**ME (°C)**		**MAE (°C)**		**MAPE**	
Temperature	**Jan**	0.99	0.99	1	1	0.99	0.99	0	0.06	0.21	0.21	0.02	0.02
	Feb	0.99	1.00	1	1	0.99	1.00	0	0.02	0.18	0.16	0.01	0.01
	Mar	0.99	0.99	1	1	0.99	0.99	0	0.03	0.15	0.13	0.01	0.01
	Apr	0.98	0.98	1	1	0.98	0.98	0	0.03	0.15	0.16	0.01	0.01
	May	0.94	0.94	1	1	0.94	0.94	0	-0.01	0.15	0.18	0.01	0.01
	Jun	0.78	0.81	1	1	0.78	0.81	0	-0.02	0.13	0.15	0.01	0.01
	Jul	0.62	0.62	1	1	0.62	0.62	0	-0.01	0.12	0.15	0.00	0.01
	Agu	0.82	0.84	1	1	0.82	0.84	0	0	0.12	0.15	0.00	0.01
	Sep	0.96	0.95	1	1	0.96	0.95	0	0.02	0.15	0.18	0.01	0.01
	Oct	0.98	0.98	1	1	0.98	0.98	0	0.09	0.20	0.23	0.01	0.01
	Nov	0.99	0.99	1	1	0.99	0.99	0	0.09	0.23	0.23	0.01	0.01
	Dec	0.99	0.99	1	1	0.99	0.99	0	0.09	0.24	0.23	0.02	0.02

In the state of Florida, there is a wide variation in the monthly risk for psyllid occurrence for the threshold of 1 and 2 psyllids per block (Figure 13). In the months of January (Figure 13A) and February (Figure 13B), the risk is low in the south and in the other regions predominates the very low risk. In March (Figure 13C), the risk rises, with medium risk predominating in the south and central part of the state, whereas in the north the risk remains very low. In April (Figure 13D), the risk rises again, with a small area of high risk being observed in the extreme southeast, with the other regions of the sate presenting medium risk in the center-south and between very low and low risks in the north. From May to August (Figures 13E, 13F, 13G, 13H), high and very high risks for psyllid occurrence are predominant, with few exceptions. In September (Figure 13I), the risks start to decline, with the medium one occurring in almost all state, with exception only for the shore areas of the Atlantic Ocean and of the north part of the Gulf of Mexico, where high risk remains. From October (Figure 13J) to December (Figure 13L), the risks for psyllid occurrence decreases gradually till reach similar conditions observed in the beginning of the year. When using the thresholds of 3 and 4 psyllids per block, very similar risk maps were obtained for the state of Florida (Figure 14), as also observed for São Paulo, Brazil (Figures 11 and 12).

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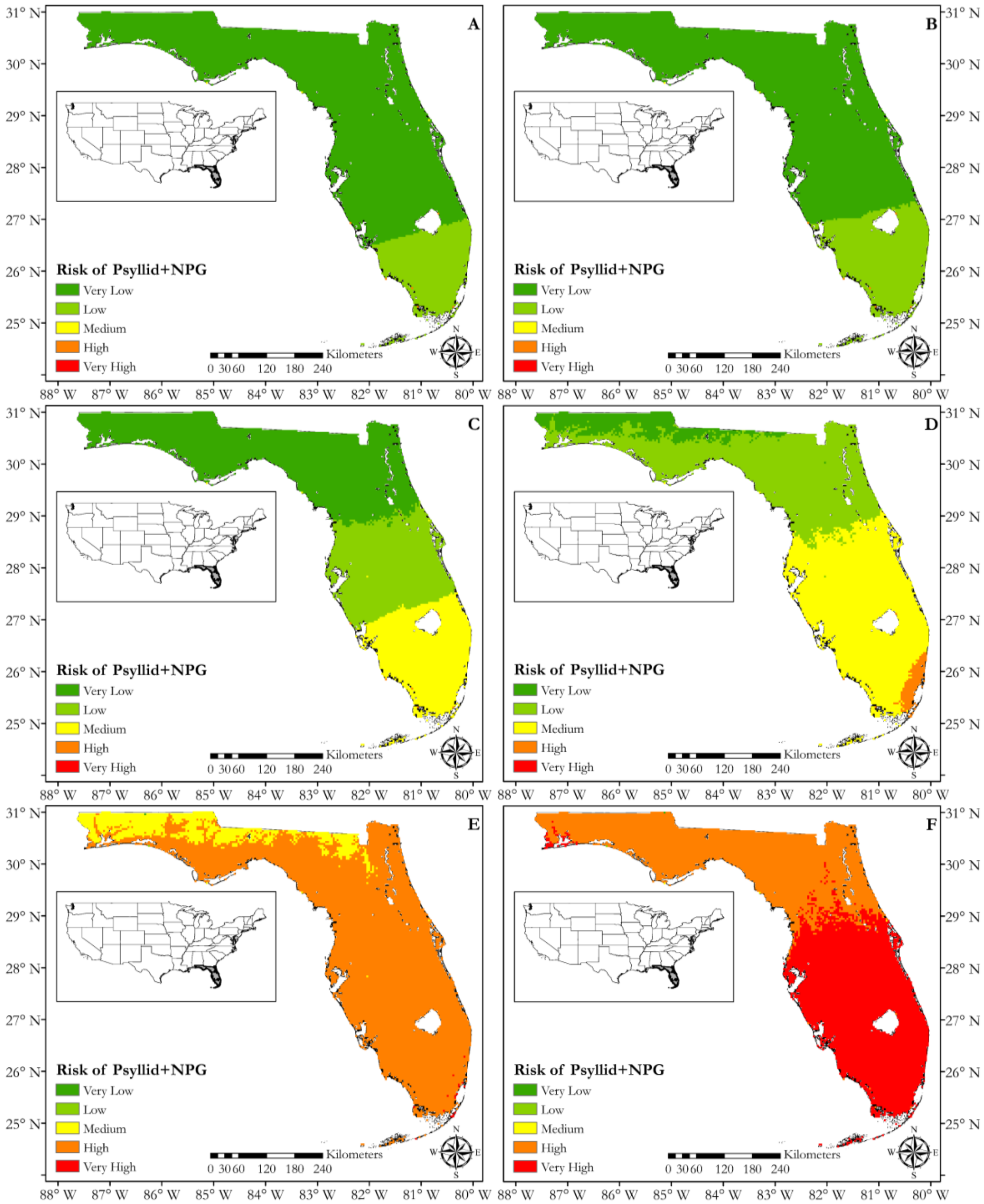

Figure 13. Average monthly Asian psyllid occurrence risk in the state of Florida, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

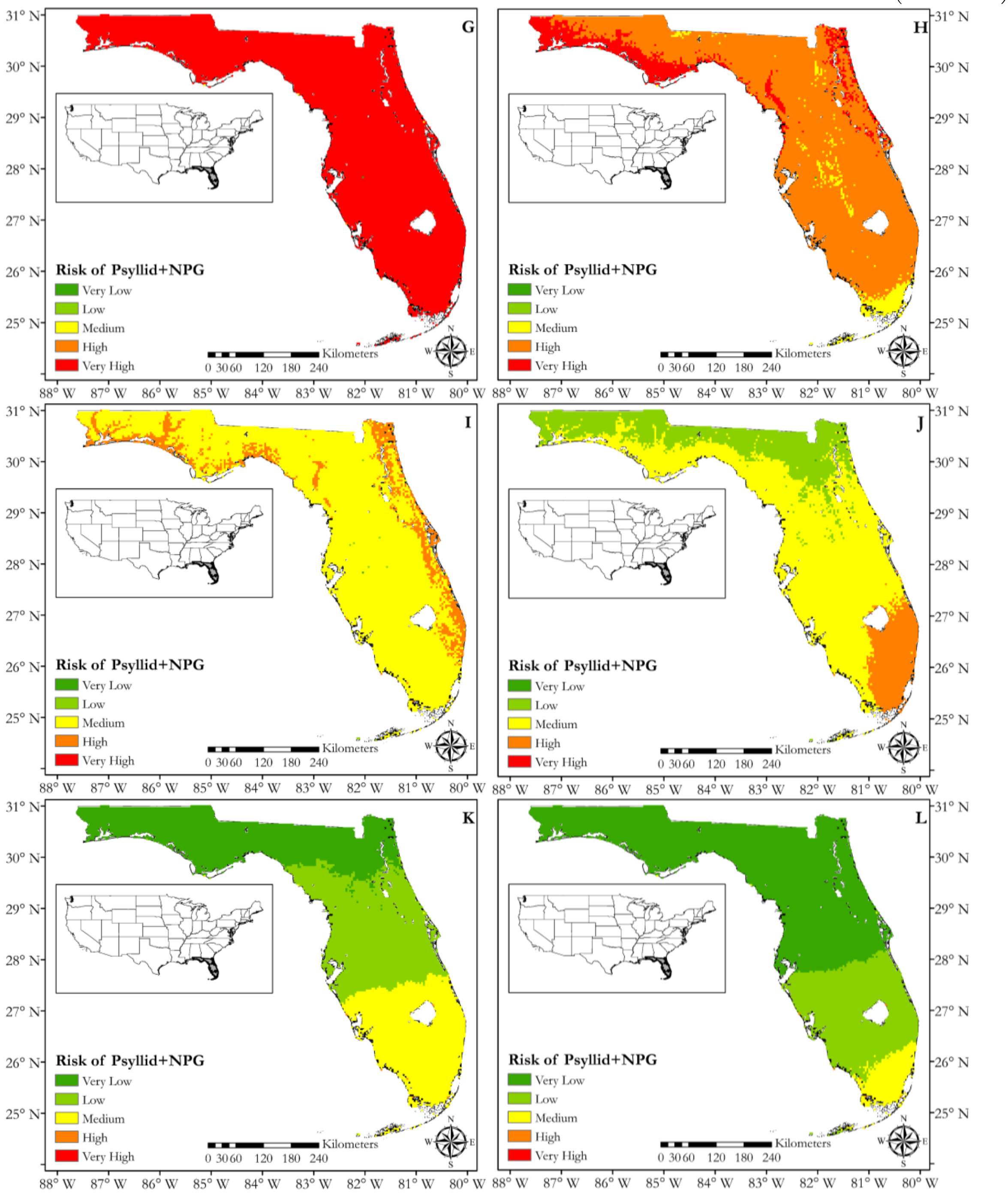

Figure 13. Average monthly Asian psyllid occurrence risk in the state of Florida, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

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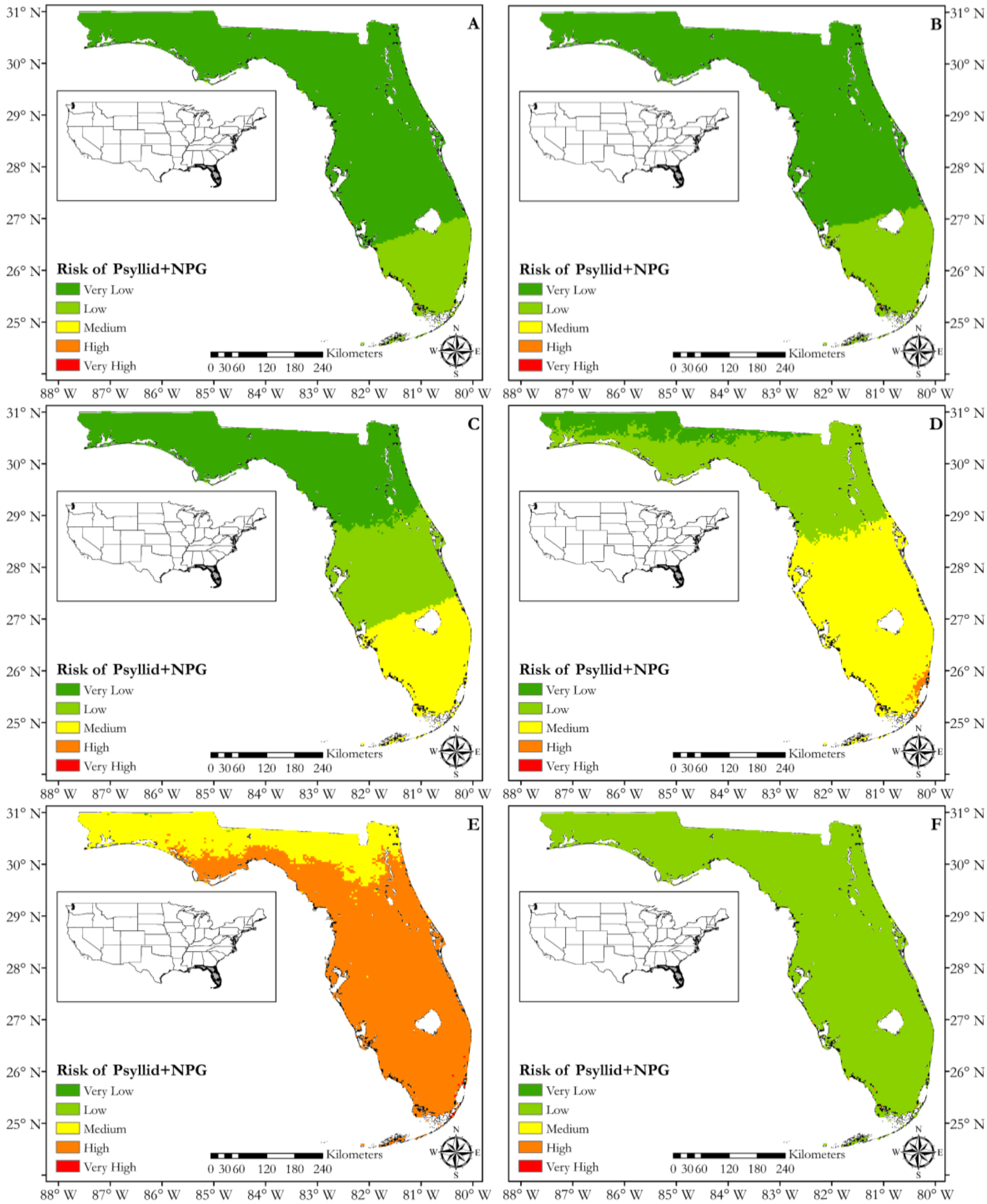

Figure 14. Average monthly Asian psyllid occurrence risk in the state of Florida, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

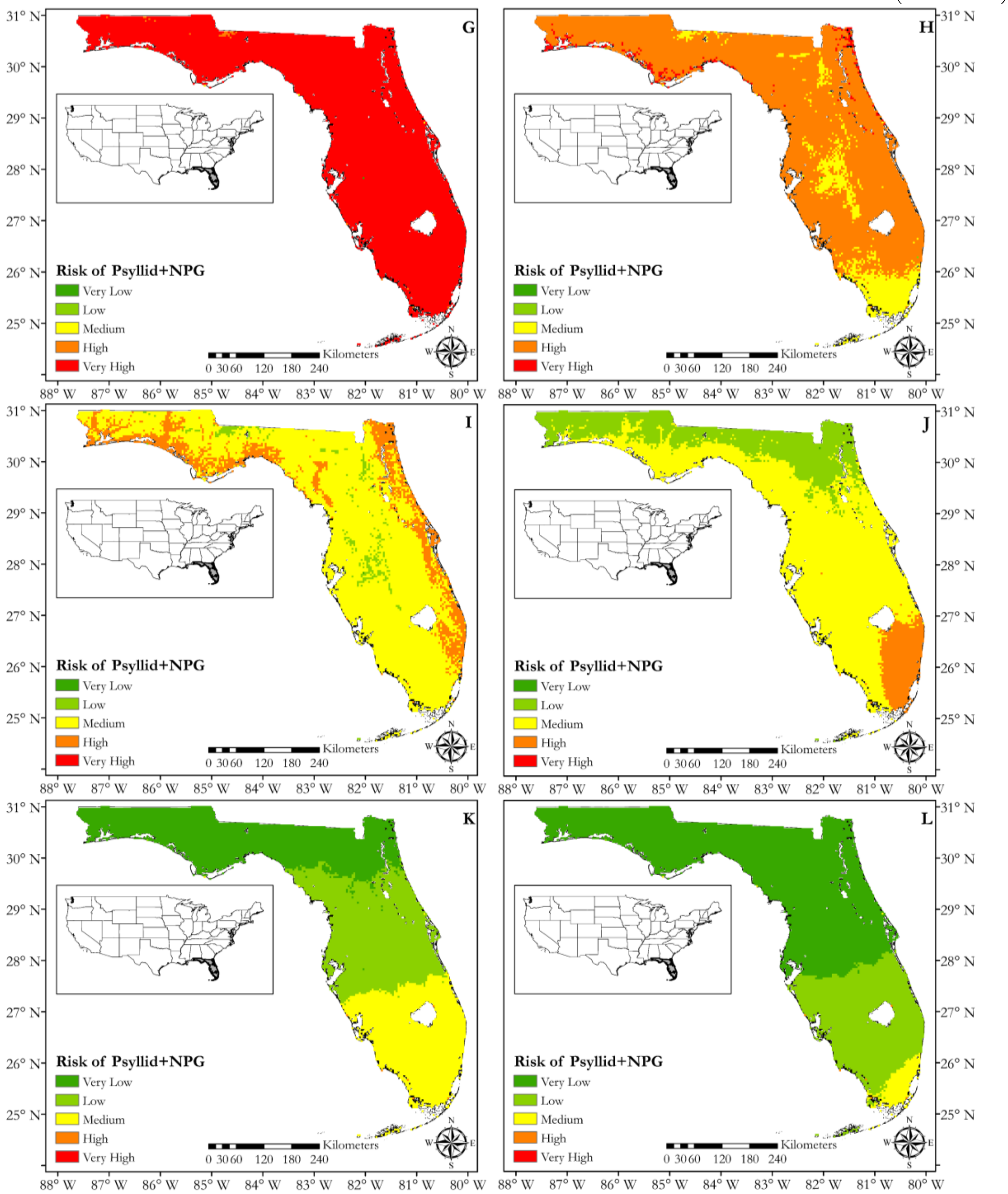

Figure 14. Average monthly Asian psyllid occurrence risk in the state of Florida, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

For the State of Texas, the performance of the multiple linear models used to spatialize monthly psyllid risk of occurrence was very good, with similar indices and errors for both thresholds used (Table 9), with exception for the month of October, which presented the lowest precision (*r* between 0.10 and 0.340) and accuracy (*d* between 0.41 and 0.62). However, for the percentage of hits even in this month the results were satisfactory, with the proportion of correct estimates ranging from 71 to 100%. For the temperature multiple linear model, the results showed an outstanding performance, with $r \geq 0.85$, $d \geq 0.92$, $c \geq 0.78$, ME ≈ 0 ºC, MAE ≤ 0.51 ºC, and MAPE ≤ 6% (Table 9).

Table 9. Statistical analysis of the average monthly Asian psyllid occurrence risk (R) maps for the thresholds of 1 and 2 psyllids per block and 3 and 4 psyllids per block, as well as for the average temperature maps, used to calculate the number of psyllids generations with degree-days approach, considering the correlation coefficient (*r*), Willmott agreement index (*d*), confidence index (*c*), mean error (ME), mean absolute error (MAE), mean absolute percentage error (MAPE) and percentage of hits [Hit (%)], during the calibration (Cal.) and validation (Val.) phases of the maps for the state of Texas, USA.

Thresholds	Months	*r*		*d*		*c*		ME (R)		MAE (R)		Hit (%)	
		Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.
1 or 2 psyllids	Jan	0.84	0.89	0.92	0.94	0.77	0.84	-0.06	0	0.26	0.09	90	92
	Feb	0.93	1.00	0.96	1.00	0.89	1.00	0.03	0	0.12	0	95	100
	Mar	0.91	0.95	0.95	0.97	0.87	0.93	0.01	-0.01	0.37	0.10	86	91
	Apr	0.87	0.87	0.93	0.93	0.81	0.81	-0.15	-0.10	0.59	0.28	79	76
	May	0.71	0.76	0.84	0.87	0.59	0.66	-0.07	-0.07	0.54	0.25	79	78
	Jun	0.58	0.52	0.79	0.76	0.45	0.39	0.06	0.04	0.53	0.31	80	72
	Jul	0.73	0.71	0.86	0.85	0.63	0.60	0.06	0.03	0.59	0.32	77	71
	Agu	0.91	0.90	0.95	0.95	0.87	0.86	-0.04	-0.07	0.37	0.22	86	80
	Sep	0.80	0.78	0.89	0.88	0.71	0.69	-0.04	0.04	0.25	0.16	90	86
	Oct	0.25	0.10	0.54	0.41	0.13	0.04	-0.25	-0.13	0.46	0.19	82	83
	Nov	0.81	0.75	0.90	0.86	0.73	0.64	-0.03	0.04	0.38	0.22	85	80
	Dec	0.87	0.91	0.93	0.95	0.82	0.87	-0.16	-0.09	0.63	0.21	76	82
3 or 4 psyllids	Jan	0.82	0.87	0.90	0.92	0.74	0.81	-0.07	0.01	0.25	0.10	90	91
	Feb	0.90	0.95	0.94	0.98	0.85	0.93	0.03	0	0.15	0.03	94	97
	Mar	0.90	0.93	0.95	0.96	0.85	0.90	0.01	-0.06	0.43	0.15	84	87
	Apr	0.89	0.84	0.94	0.91	0.84	0.77	-0.10	-0.13	0.49	0.31	82	75
	May	0.70	0.79	0.83	0.89	0.59	0.70	-0.03	0.04	0.62	0.25	76	78
	Jun	0.75	0.80	0.87	0.90	0.65	0.72	0.16	-0.04	0.34	0.13	87	88
	Jul	0.72	0.79	0.84	0.89	0.61	0.70	0.15	-0.04	0.62	0.22	76	80
	Agu	0.91	0.92	0.95	0.96	0.87	0.88	-0.01	-0.01	0.37	0.19	86	83
	Sep	0.85	0.86	0.92	0.92	0.77	0.79	0.07	0.04	0.19	0.10	93	91
	Oct	0.31	0.34	0.62	0.62	0.20	0.21	-0.26	-0.16	0.65	0.25	75	78
	Nov	0.79	0.81	0.89	0.90	0.70	0.72	-0.09	0.06	0.44	0.18	83	84
	Dec	0.88	0.91	0.93	0.95	0.82	0.87	-0.09	-0.06	0.62	0.21	76	82
		r		*d*		*c*		ME (ºC)		MAE (ºC)		MAPE	
Temperature	Jan	0.99	0.99	1.00	1.00	0.98	0.99	0	-0.03	0.32	0.33	0.05	0.06
	Feb	0.99	0.99	1.00	1.00	0.98	0.99	0	-0.06	0.31	0.31	0.03	0.04
	Mar	0.98	0.99	0.99	0.99	0.98	0.99	0	-0.04	0.34	0.34	0.02	0.03
	Apr	0.97	0.98	0.99	0.99	0.96	0.98	0	-0.07	0.40	0.41	0.02	0.02
	May	0.95	0.97	0.98	0.99	0.93	0.96	0	-0.11	0.43	0.44	0.02	0.02
	Jun	0.90	0.96	0.95	0.97	0.86	0.93	0	-0.09	0.43	0.41	0.02	0.02
	Jul	0.85	0.93	0.92	0.96	0.78	0.89	0	-0.03	0.46	0.44	0.02	0.02
	Agu	0.88	0.95	0.94	0.97	0.83	0.93	0	-0.06	0.51	0.46	0.02	0.02
	Sep	0.95	0.98	0.98	0.99	0.93	0.97	0	-0.04	0.38	0.36	0.02	0.02
	Oct	0.97	0.99	0.99	0.99	0.96	0.98	0	-0.05	0.35	0.34	0.02	0.02
	Nov	0.98	0.99	0.99	1.00	0.98	0.99	0	-0.02	0.35	0.33	0.03	0.03
	Dec	0.99	0.99	1.00	1.00	0.98	0.99	0	-0.03	0.34	0.32	0.05	0.05

In the state of Texas, the monthly risks for psyllid occurrence for the threshold of 1 and 2 captures per block varies along the year, in a similar way as observed for Florida. The risks are very low in almost the entire state in January (Figure 15A), February (Figure 15B), March (Figure

15C), November (Figure 15K), and December (Figure 15L). For the other months of the year for the same threshold presented above, the risks vary substantially, with the areas of highest risks in certain months being in the south of the state, as from April to June (Figures 15D, 15E, 15F) and September (Figure 15I) and October (Figure 15J), and in others in the center-north region, as in the months of July (Figure 15G) and August (Figure 15H). Similar maps for psyllid occurrence risk were obtained for the threshold of 3 and 4 psyllids per block (Figure 16), as also observed for São Paulo and Florida.

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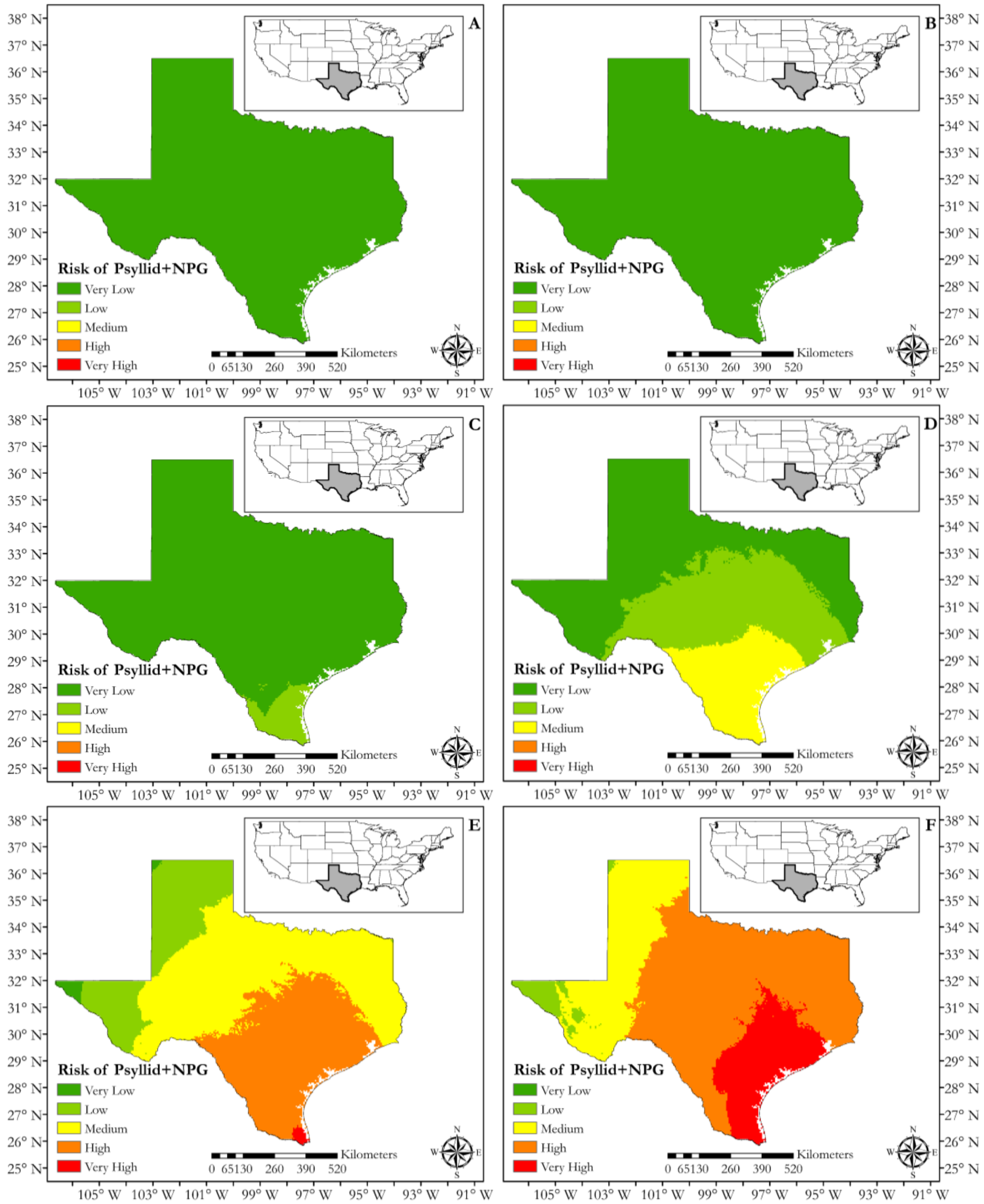

Figure 15. Average monthly Asian psyllid occurrence risk in the state of Texas, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

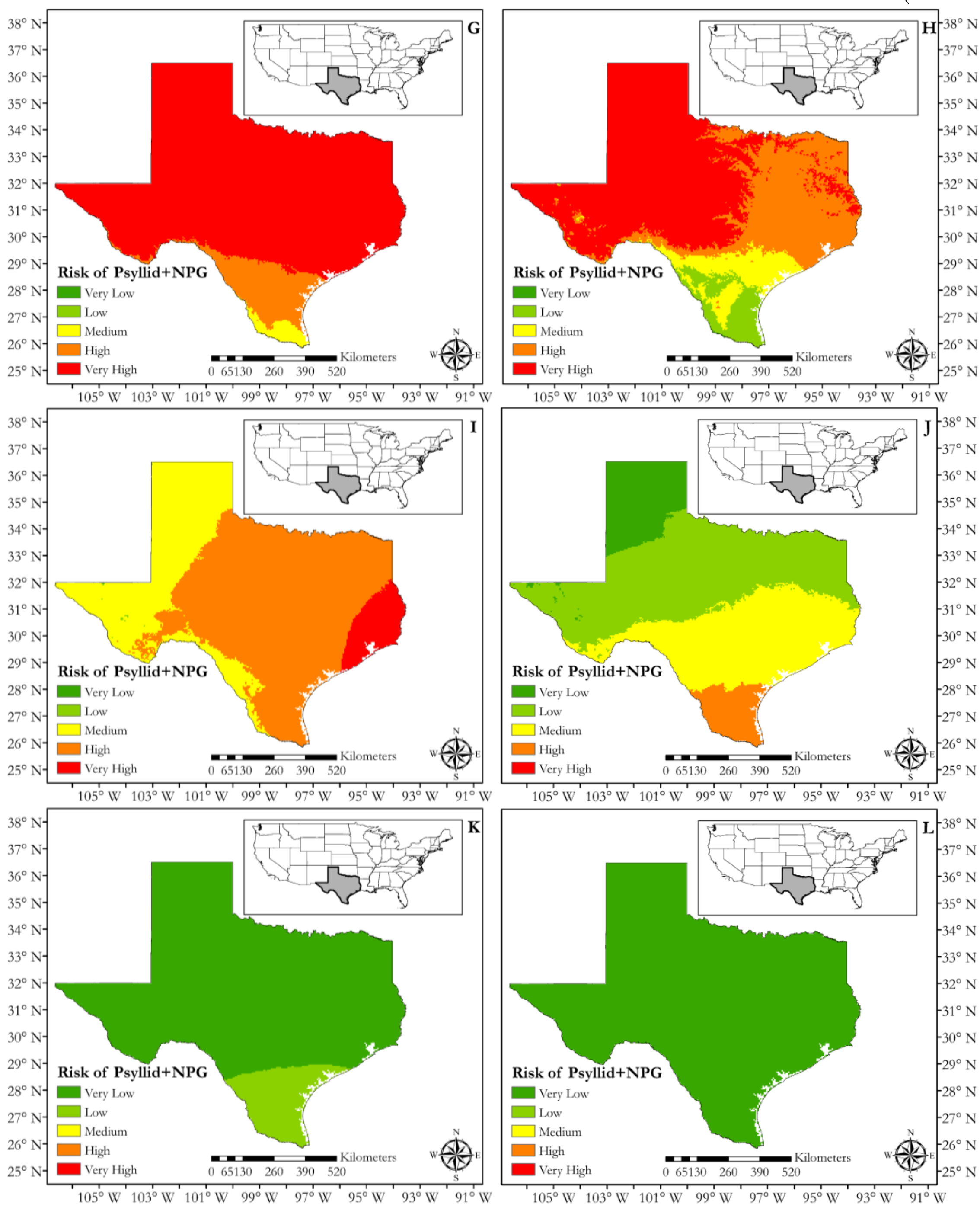

Figure 15. Average monthly Asian psyllid occurrence risk in the state of Texas, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

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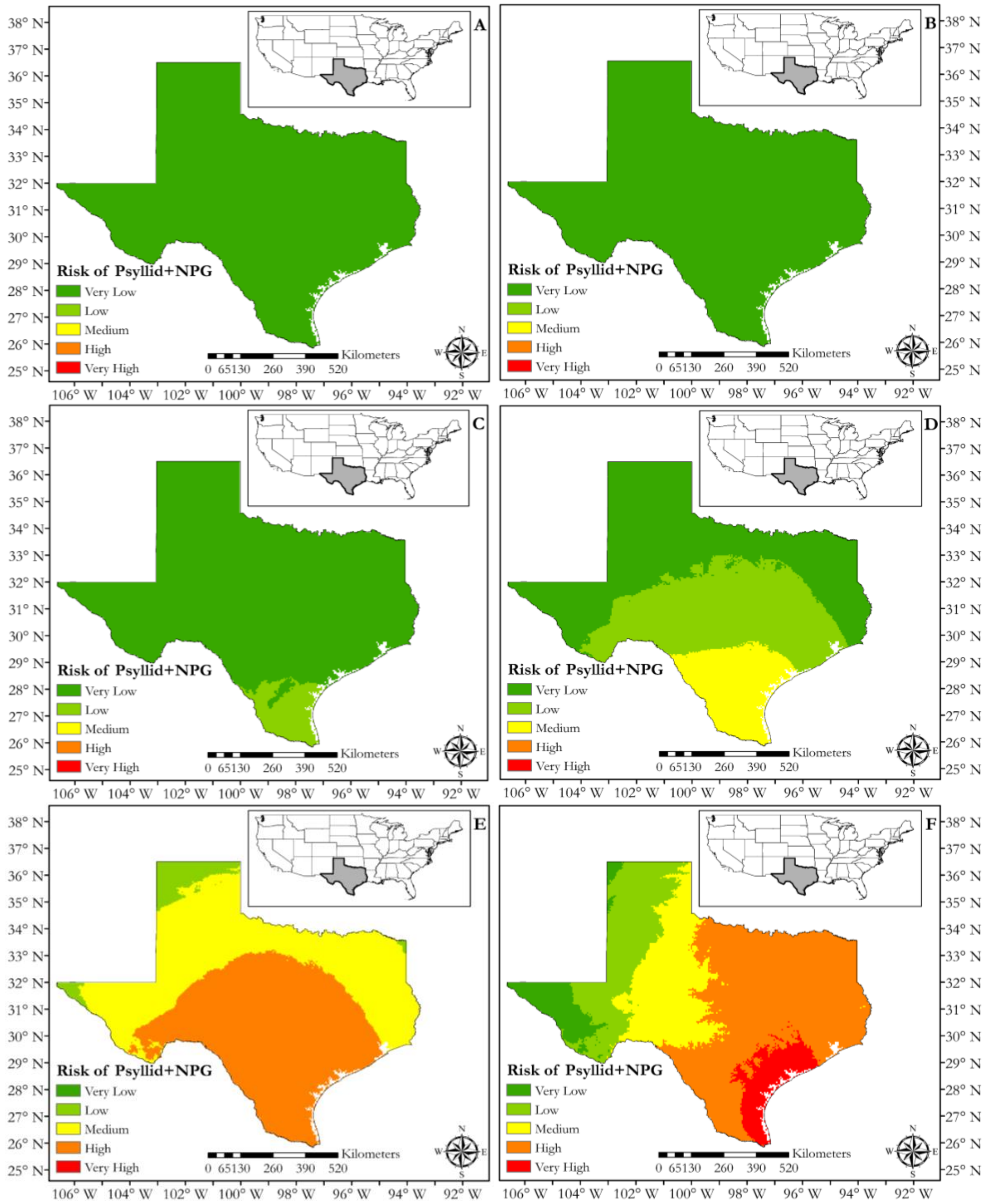

Figure 16. Average monthly Asian psyllid occurrence risk in the state of Texas, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

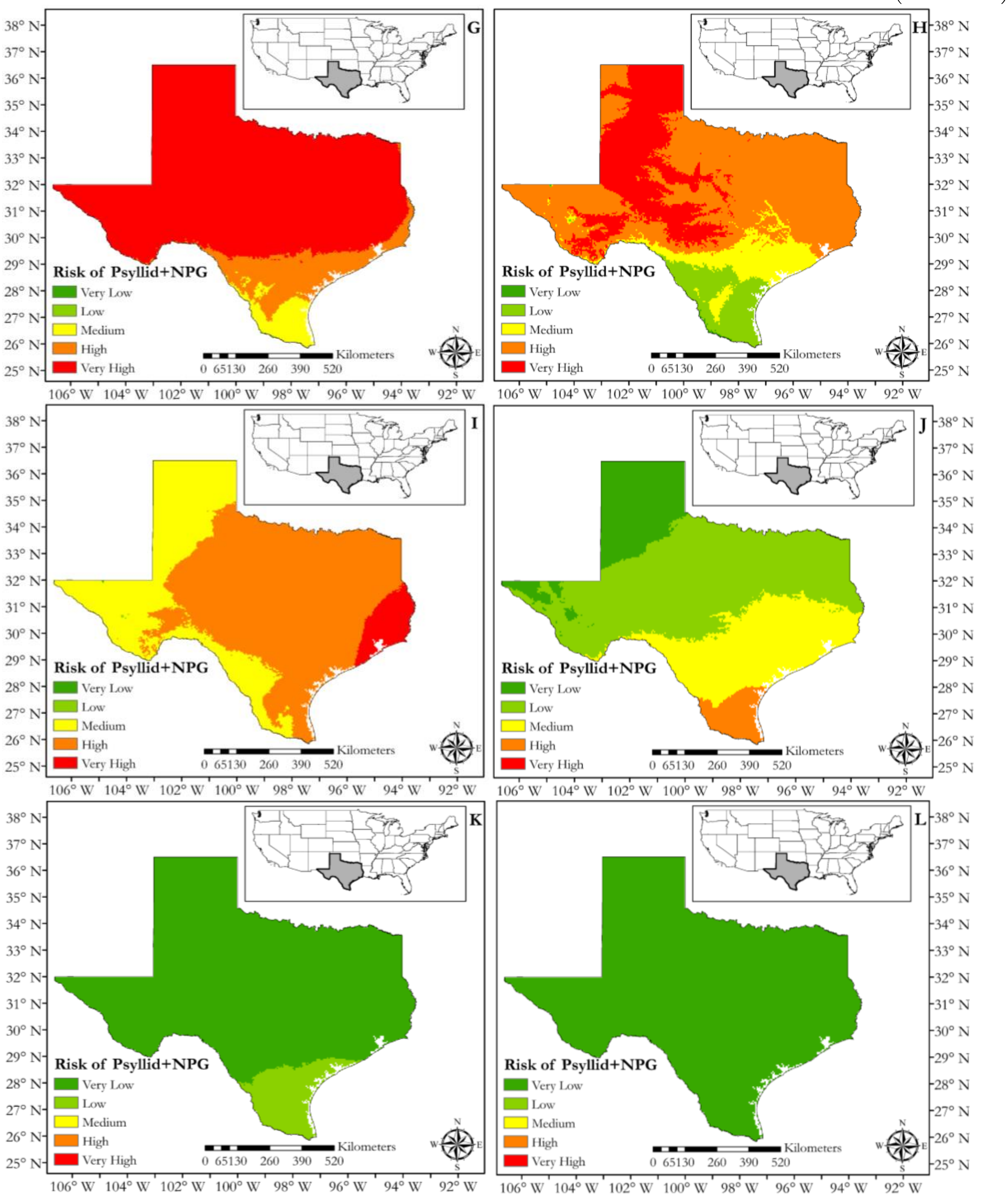

Figure 16. Average monthly Asian psyllid occurrence risk in the state of Texas, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

Table 10 presents the performance of the multiple linear models used to spatialize the monthly risk and temperature for the state of California (Table 10). For both thresholds considered, all the monthly models to spatialize the risks was just reasonable, with a wide range of indices of precision and accuracy. For the threshold of 1 and 2 psyllids per block the *r* ranged from 0 to 0.93, *d* varied between 0 and 0.96, whereas *c* oscillated between 0 and 0.89. Despite the reasonable performance in term of the statistical indices, the percentage of hits ranged from 69 to 100%, which reflects a good performance for estimating the risks. For the threshold of 3 and 4 psyllids per block, the performance was similar, with *r* between 0 and 0.87, *d* ranging from 0 to 0.93, and *c* varying between 0 and 0.81. Also, the percentage of correct hits was very similar, ranging from 62 to 100%. For air temperature multi linear models, the performance was excellent for all months, as presented in Table 10, with $r \geq 0.84$, $d \geq 0.90$, $c \geq 0.76$, and errors of low magnitude.

Table 10. Statistical analysis of the average monthly Asian psyllid occurrence risk (R) maps for the thresholds of 1 and 2 psyllids per block and 3 and 4 psyllids per block, as well as for the average temperature maps, used to calculate the number of psyllids generations with degree-days approach, considering the correlation coefficient (*r*), Willmott agreement index (*d*), confidence index (*c*), mean error (ME), mean absolute error (MAE), mean absolute percentage error (MAPE) and percentage of hits [Hit (%)], during the calibration (Cal.) and validation (Val.) phases of the maps for the state of California, USA.

Thresholds	Months	*r*		*d*		*c*		ME (R)		MAE (R)		Hit (%)	
		Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.
1 or 2 psyllids	Jan	0	0	0.07	0	0	0	0.03	0	0.03	0	98	100
	Feb	0	0	0.07	0	0	0	0.03	-0.02	0.03	0.02	98	98
	Mar	0.93	0.85	0.96	0.90	0.89	0.77	0	-0.06	0.03	0.06	98	94
	Apr	0.71	0.76	0.85	0.88	0.60	0.66	0.04	0.02	0.37	0.15	78	85
	May	0.73	0.58	0.84	0.75	0.61	0.43	-0.07	-0.17	0.51	0.42	69	63
	Jun	0.79	0.47	0.88	0.67	0.70	0.31	-0.13	-0.17	0.46	0.42	73	69
	Jul	0.78	0.65	0.88	0.80	0.68	0.52	-0.04	0.06	0.37	0.35	78	71
	Agu	0.79	0.74	0.88	0.85	0.69	0.63	-0.03	0	0.50	0.25	70	79
	Sep	0.74	0.59	0.85	0.76	0.63	0.45	-0.13	0.04	0.51	0.33	69	71
	Oct	0.73	0.52	0.85	0.74	0.61	0.38	-0.01	0.02	0.34	0.31	80	73
	Nov	0.65	0.52	0.74	0.72	0.48	0.38	0.21	-0.02	0.47	0.31	73	75
	Dec	0.57	0.71	0.72	0.82	0.41	0.59	0.07	0.04	0.16	0.08	90	92
3 or 4 psyllids	Jan	0	0	0.07	0	0	0	0.03	0	0.03	0	98	100
	Feb	0	0	0.07	0	0	0	0.03	0	0.03	0	98	100
	Mar	0.87	0.86	0.93	0.92	0.81	0.79	-0.01	-0.04	0.04	0.04	97	96
	Apr	0.69	0.79	0.84	0.89	0.58	0.70	-0.04	0.04	0.34	0.13	80	88
	May	0.66	0.61	0.79	0.77	0.52	0.46	-0.10	-0.17	0.63	0.38	62	67
	Jun	0.76	0.36	0.85	0.60	0.65	0.21	-0.13	-0.13	0.51	0.42	69	69
	Jul	0.76	0.69	0.86	0.82	0.65	0.56	-0.12	0.02	0.41	0.35	75	69
	Agu	0.80	0.67	0.89	0.81	0.72	0.54	-0.06	0.02	0.44	0.27	73	79
	Sep	0.74	0.59	0.86	0.76	0.63	0.45	-0.16	0.04	0.51	0.33	69	71
	Oct	0.75	0.42	0.85	0.66	0.64	0.28	-0.06	0.06	0.32	0.35	81	69
	Nov	0.62	0.56	0.72	0.73	0.44	0.41	0.18	-0.04	0.50	0.33	70	71
	Dec	0.69	0.71	0.78	0.82	0.54	0.59	0.10	0.04	0.13	0.08	92	92
		r		*d*		*c*		ME (°C)		MAE (°C)		MAPE	
Temperature	Jan	0.94	0.95	0.97	0.97	0.92	0.93	0	0.34	1.11	1.07	0.44	0.40
	Feb	0.97	0.97	0.99	0.99	0.96	0.96	0	0.17	0.85	0.86	0.35	1.39
	Mar	0.98	0.97	0.99	0.98	0.97	0.95	0	0.12	0.80	0.96	0.54	0.16
	Apr	0.97	0.95	0.98	0.97	0.96	0.92	0	0.03	1.00	1.27	0.16	0.19
	May	0.95	0.92	0.97	0.95	0.92	0.88	0	-0.14	1.30	1.70	0.10	0.12
	Jun	0.92	0.88	0.96	0.93	0.88	0.82	0	-0.39	1.62	2.05	0.09	0.12
	Jul	0.88	0.84	0.93	0.90	0.82	0.76	0	-0.40	1.84	2.25	0.09	0.11
	Agu	0.89	0.85	0.94	0.91	0.83	0.77	0	-0.28	1.76	2.16	0.08	0.11
	Sep	0.91	0.87	0.95	0.93	0.87	0.81	0	-0.07	1.54	1.84	0.08	0.10
	Oct	0.95	0.93	0.97	0.96	0.92	0.90	0	0.10	1.18	1.31	0.09	0.09
	Nov	0.96	0.97	0.98	0.98	0.94	0.95	0	0.25	0.98	0.96	0.19	0.14
	Dec	0.95	0.96	0.97	0.98	0.93	0.94	0	0.34	1.03	1.01	0.31	0.26

The monthly maps of psyllid occurrence risk for the state of California (Figure 17) show that most of the months has predominantly very low risk for the threshold of 1 and 2 psyllids captured per block. The only month for such threshold with higher risks is September when the risk for psyllid occurrence reaches medium to high in the south of the state (Figure 17I). For the other months of the year, January (Figure 17A), February (Figure 17B), and March (Figure 17C) present low risk across the state. In April (Figure 17D), the risk rises in the southeastern and in a small area in the east of the state, where low risk is observed, whereas in other regions of California very low risk predominate. In May (Figure 17E), areas with low risk rise in the state, with areas with medium risk in the southeastern, central, and eastern regions, whereas in most of the state very low risk continue to prevail. In June (Figure 17F), the risk rises again, but the very low condition occurs in the major parts of the state. In the July and August (Figures 17G and 17H), the psyllid risk decreases gradually, but in September, as already mentioned it increases becoming the month with the highest risk for psyllid captures. After that, from October to December (Figures 17J and 17K), the very low risk dominates all the state, with exception for the extreme south in October, where the risk is low.

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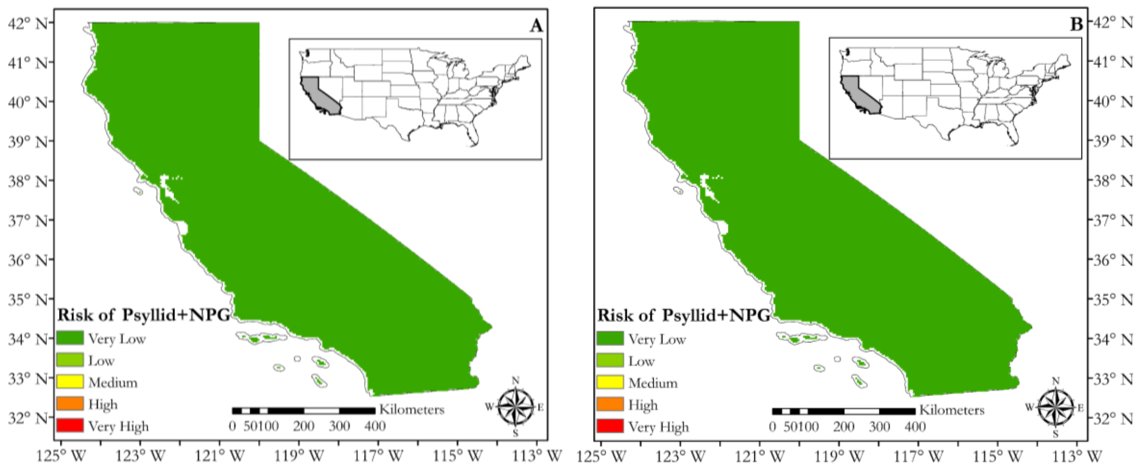

Figure 17. Average monthly Asian psyllid occurrence risk in the state of California, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

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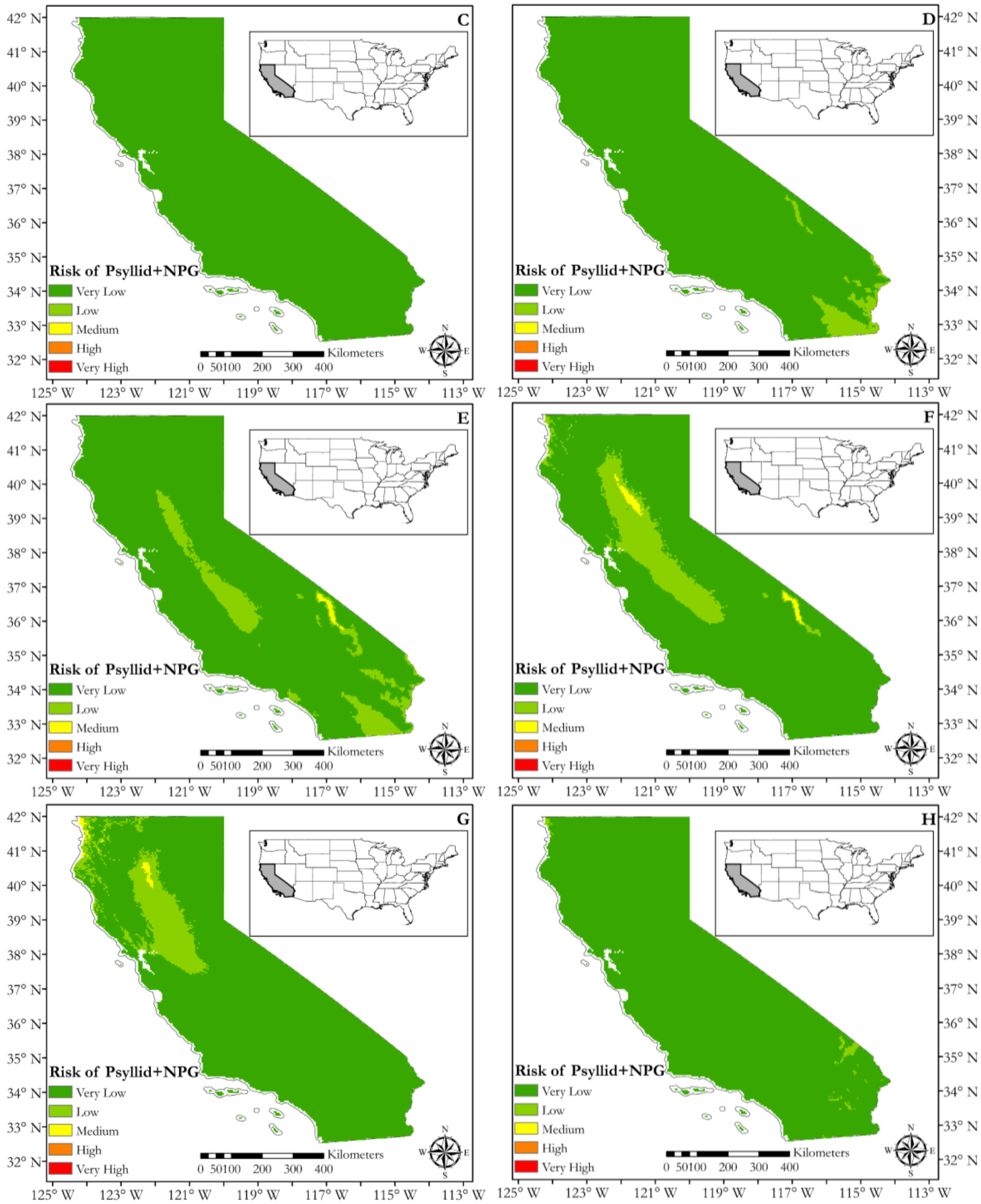

Figure 17. Average monthly Asian psyllid occurrence risk in the state of California, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

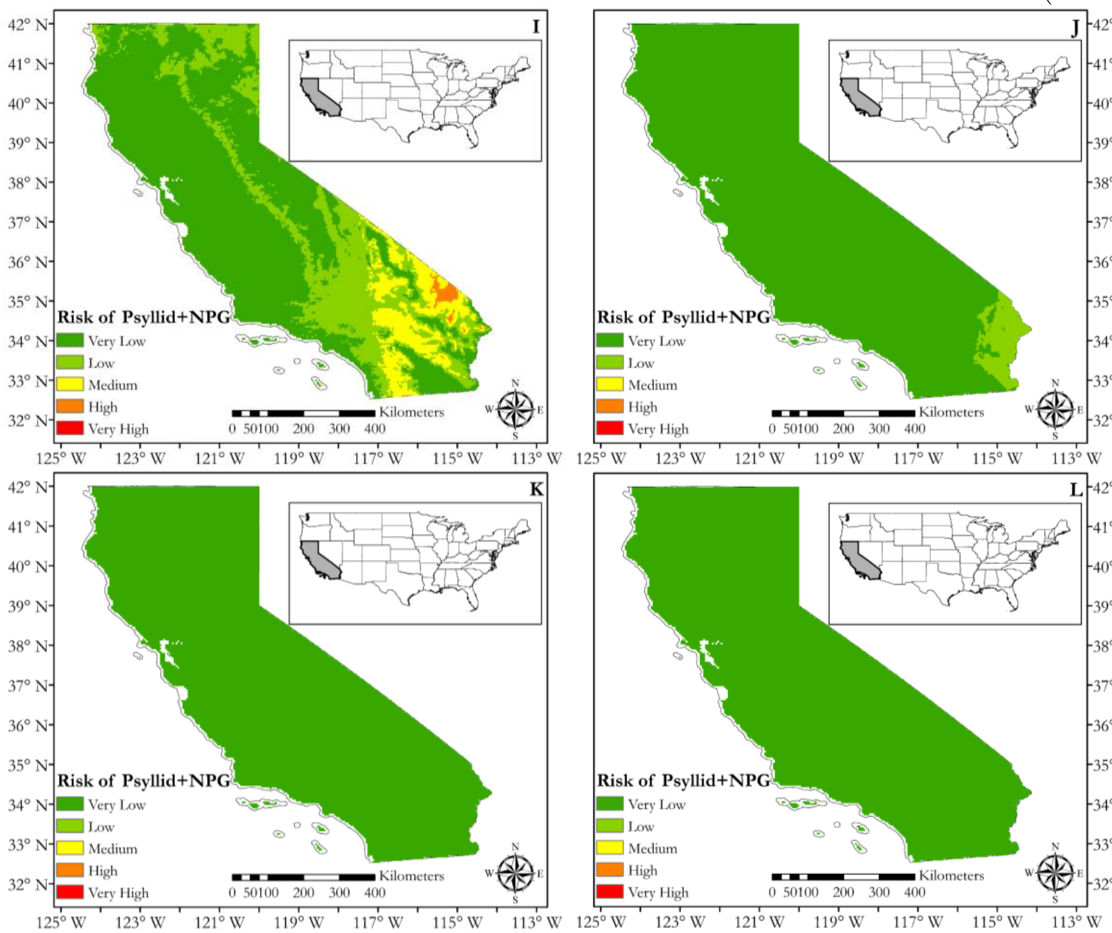

Figure 17. Average monthly Asian psyllid occurrence risk in the state of California, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

For the threshold of 3 and 4 psyllids per block (Figure 18), the risks for psyllid occurrence changed a bit, however keeping the same tendency observed for the threshold of 1 and 2 psyllids per block (Figure 17). From January (Figure 18A) to April (Figure 18D) and from August (Figure 18H) to December (Figures 18L), there is a predominance of very low risk. From May (Figure 18E) to July (Figure 18G), the risks increase gradually, reaching the maximum values in July, when risks vary between very low to high.

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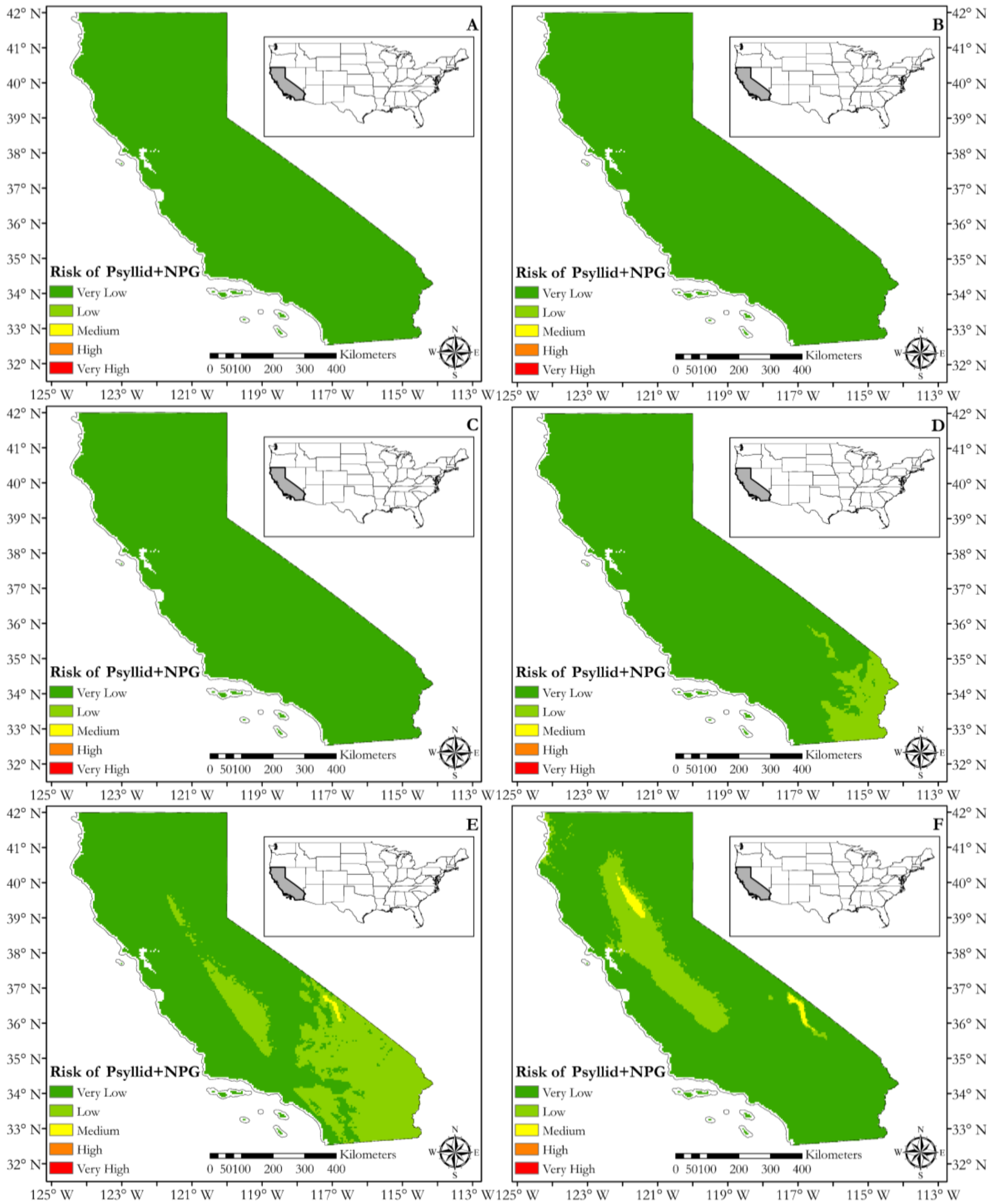

Figure 18. Average monthly Asian psyllid occurrence risk in the state of California, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

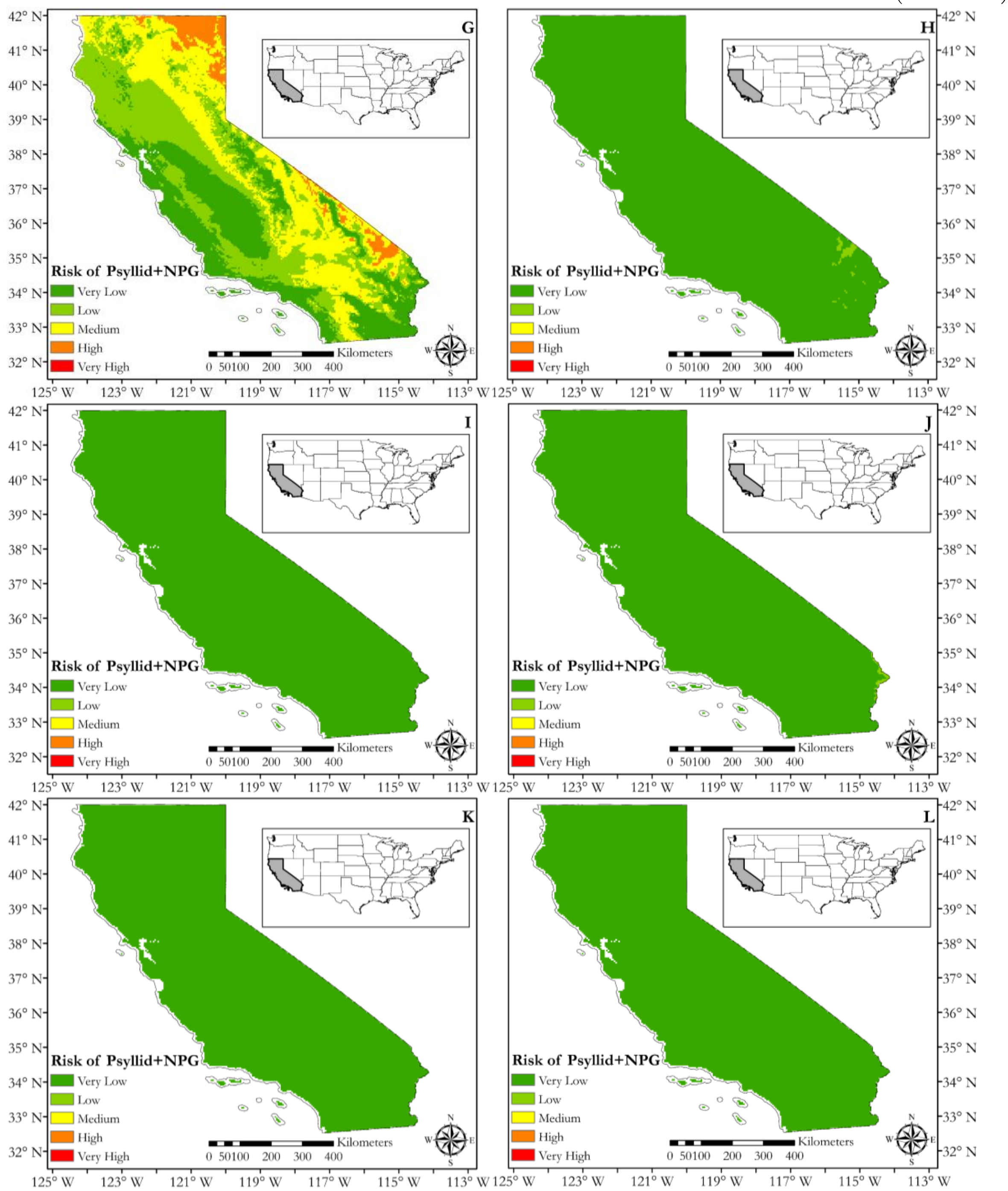

Figure 18. Average monthly Asian psyllid occurrence risk in the state of California, USA, based on the combination of the number of sprays model and the number of psyllid generations (NPG), determined by degree-days, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

3.4. Discussion

The spatialization of the climatic risk for psyllid occurrence by coupling the agroclimatic model for estimated citrus sprouting and the number of psyllid generations, calculated by degree-days, were efficient for mapping the risks of potential for HLB disease. Firstly, climate-based spatialized psyllid occurrence risk assessment can help growers and consultants to plan the cultivation of new citrus orchards with less risk for HLB in the assessed states, using both annual and monthly maps. Secondly, these risk maps can help growers and technical staff in the planning chemical control by knowing which months are of higher risk for psyllid outbreaks and thus HLB infection.

The model used for determining psyllid occurrence risks was based on the favorable climatic conditions for estimated new sprouts emissions, which are the most attractive conditions for psyllid outbreaks, since they favor development of the nymphal stages (Parra et al. 2010). Sprouting is stimulated when rainfall occurs after a drought period (Ramos, et al. 2010). In addition to the water deficit, the proposed model considered the temperatures between 16 and 28 °C, which according to Lee et al. (2015) imply in modifications on the state of the tissues, making them become less tender for the insects, difficulting feeding, especially in the initial stages of vector development, as well as the transmission of the bacteria. This temperature range is close to the most favorable for psyllid development reports by Nava et al. (2007), which is between 18 to 30 °C.

Among the four states assessed in this study, Florida was the one with the highest risk of psyllid occurrence, whereas in Texas and California were those with the lowest ones. In the state of São Paulo, there are higher risks for psyllid occurrence than in Texas and California, but they are lower than in Florida. However, it is important to note that the model does not consider irrigation, which can change the risks obtained for all these states.

The main factors to explain the psyllid population dynamic are those related to the climate conditions that affect both citrus sprouting and psyllid development. For psyllid development, temperature is the most important, once higher the air temperature, faster is the psyllid development and shorter its life cycle, generating a new population (PARRA et al., 2010; NAROUEI-KHANDAN et al., 2016; RAMIREZ et al., 2016). Rainfall after a period of water deficit promotes new citrus sprouting, which attracts the vector for feeding and oviposition (RAMOS et al., 2010; TORRES-PACHECO et al., 2013; DAVIES; ALBRIGO, 1994). Both of these two variables (air temperature and rainfall) vary spatially and temporally within each state, which explain the patterns of psyllid occurrence risk observed in the present study.

The risks of psyllid occurrence can help growers to determine how many insecticide applications their orchards are likely to need per year, the months that requires more attention, and how much insecticide will be necessary to buy. The model used here considered an interval of capture of 7 days, which agrees with the interval of actions of the majority of the insecticides. Therefore, when using the model for timing chemical control, the plants will be always protected. Assato (2018) evaluated a period between applications of 13 days for psyllid control in citrus and found that such period was too long for an effective psyllid control, since the plants can grow in this interval of time generating new tissues that will not be protected by the previous spray. Another aspect is that 15 days can be enough to complete the 5 instars of Asian citrus psyllid (NAVA et al., 2007), whereas the transmission of the HLB bacterium requires between 11 and 33 days after acquisition of the pathogen by the psyllid (CANALE et al., 2016). Although the 7-day interval between sprays can be considered short, it may be valuable for regions or seasons when there is a high risk of psyllid occurrence and pathogen transmission.

When analyzing the annual risks by region within the states of the northern hemisphere, Florida, Texas and California (Figures 8, 9 and 10), they were greater in the south and center, whereas for São Paulo, they were greater in the northwest and center regions of the state (Figure 7). When analyzing the last five years for these states (Figures 3, 4, 5 and 6), most of them show changes. For the state of São Paulo, the risks increase in the east and decreases in the north. In the last five years for the state of Florida, the risks did not change when compared to Texas and California, where the risks were higher in the center and south for the first and decreased in the last. These results show that the risks have been changing over the years, probably caused by changes in temperature, rainfall patterns and management (DUFEK; AMBRIZI, 2008; FANTE; NETO, 2017).

In the state of São Paulo, the monthly risk was lower in the southern part than in the north. This is due to lower temperature and water deficit and high rainfall in the southern regions, which result in conditions that are less favorable for psyllid outbreaks. Considering temporal variation, lower risks normally occur during the wintertime in the southern hemisphere, when low temperatures and few rainfalls are observed. The highest risks in São Paulo are observed during spring and summer, which is caused by the high temperatures and enough rainfall to stimulate sprout growth. In addition, during these two seasons the higher temperatures allow more psyllid generations, one of the factors that promotes increasing risks.

According to the updated Köppen classification for Brazil (ALVARES et al., 2014), the northern region of São Paulo has the highest average temperature, and as it moves towards the coast and south, the temperature decreases. According to the same authors, rainfall has an inverse relationship, with the largest volumes recorded on the coast and south of the state, and lower values in the north and west regions. This explains why the greatest risk for psyllid occurrence is in the north of the state of São Paulo. For the period of the year with the highest risk for psyllid occurrence, spring and summer are those more suitable for the insect. It agrees with the study of Bassanezi et al. (2010), which found that the highest populations of HLB vector occur from October to January in southern Brazil.

In Florida, the lowest risk of occurrence of HLB vector is in the winter, from December to February, when lower temperatures and few rainfalls are observed. The greatest risk, on the other hand, occurs during the summer, when increasing temperatures promotes an increase in the sprouts and in the number of generations. In southern Florida, the climatic type is monsoon climate with drier winter in which the temperature is above 18 °C every month and in the rest of the state it is humid subtropical with no defined dry season and presents a cold winter (PEEL et al., 2007). This justifies the lower psyllid occurrence risk in the center and north of the state, due to the lower temperatures and rainfall during the winter, and a slightly higher risk in the south due to the warmer climate. Only in the north of the state where there is water deficit and the higher temperatures, the risks increase. Similar results were found by the study of Lewis-Rosenblum et al. (2015), which observed the highest risks for psyllid occurrence in the spring and summer months and the lowest risks from September to March.

In Texas, the risk presents a monthly variation like that presented in Florida, with the lowest risk also occurring in winter, reflecting the lower temperature and greater deficit, not accompanied by greater precipitation, in addition to the number of generations being lower due to the decrease in temperature. The risk increases in the summer due to the increase in temperature, greater rainfall in the north and greater deficit. The lower rainfall in the south justifies why the risk is lower only in the south in the months of May to August due to the lesser induction of sprouting, because although there is a water deficit, there is no stimulus to sprouting by rain, coupled with temperatures above the threshold in this part of the year in this region. The greatest risk in the south of the state in late autumn and early spring is due to the highest rainfall and deficit events still occurring during this period, and in the north the lowest risk during this period and due to the lowest temperatures.

In eastern Texas, the climate is subtropical with a cold winter and no dry season, while the west is semi-arid, with low rainfall throughout the year and very hot summers (PEEL et al., 2007). Due to the low rainfall occurring in the western part of the state, this reduces the lower risks in the annual average, as well as in most months of the year. In addition, the south of the state presents the lowest risk in the month of July compared to the north, what is justified by the high temperatures of this region. The lower risk in winter is due to the lower temperature in the east of the state, while in the west it is due to less rainfall, both reflecting the predominant climatic type of the region. Da Graça et al. (2008) also found greater risk in the south of Texas compared to the north, agreeing with what was found in the present study. For the monthly psyllid captures, the risk increases in March, with a peak occurring from May to June and extending until September. In the south, the risk of psyllid occurrence remains higher until October, with the risk being higher in the south, northwest and south-center of the state in the first semester, as observed by Flores et al. (2009), which corroborates the results obtained in the present study.

In the state of California, the lowest monthly and annual risks were observed in relation to the other American states. The main reason for the low risks in the months from December to March is due to the lower temperatures, combined with the higher rainfall in the north of the state during the winter and lower in part of the autumn, in addition to the lower water deficit during this period of the year, with less sprouts. Also, the number of generations decreases during these months. The risks of psyllid occurrence increase a bit in the summer due to the increasing temperatures and also to the higher number of vector generations. In the south of the state, the temperature is above the threshold and the risk is not high. On the other hand, in the summer the water deficit is very high reducing the sprouts mainly further north of the state. In the cold semi-arid and hot desert climates of the state of California, occurring in the east and southeast, the climates with low rainfall throughout the year, with the first having temperature below 0 °C in at least one month and an average annual temperature above 18 °C and the second with minimum temperature below or equal to 0 °C and the monthly average below 18 °C (PEEL et al., 2007), reduces the risks for psyllid occurrence. In the south of the state, the limitation for psyllid occurrence is mostly due to less rainfall while the north is more in terms of temperature, however in the north the lower temperature during the winter limits the climatic risk and the number of generations. However, the higher temperature in the summer increases the risk, mainly in the north. According to Bayles et al. (2017) and Kistner et al. (2016) the population of the HLB vector is greater in the southeastern California, where psyllid population grows in March until it reaches its peak in October, decreasing after that. These results are similar to those obtained in this study, mainly when adopting more conservative control measures (1 and 2 psyllids per block), for annual and monthly time scales. The lower risk observed in California in relation to the other assessed states of USA is due to the climatic conditions, mainly thermal limitation in the north and water deficit in the south (PEEL et al., 2007). Considering that the HLB vector was firstly recorded in the south of California in 2008 (KUMAGAI et al., 2013), until now there are still no studies that report the occurrence of the psyllid in northern California. However, according to the present study there are conditions for that in some areas both at annual and monthly time scales.

Climatic disease-risk assessment can provide useful decision aids for growers. For example, Soares-Colletti et al. (2016) evaluated the climatic risk of postbloom fruit drop (PFD) caused by *Colletotrichum acutatum* and *C. gloeosporioides* in citrus in the state of São Paulo, and Sentelhas et al. (2016) used a climate model to predict sugarcane orange rust for Brazil and Australia, both aiming to help growers and consultants in a better disease control plan. For HLB, Diaz-Padilla et al. (2014) and Torres-Pacheco et al. (2013) evaluated the risk of occurrence of the psyllid in Mexico, the first using temperature and the second on temperature and rainfall data, aiming to stablish the potential for disease occurrence. Narouei-Khandan et al. (2016) also used a climate approach to estimate the occurrence of Asian citrus psyllid and found a very good performance, with a precision of 0.969.

Most studies that assess the risk or simulate the occurrence of the psyllid do not use data observed in the field, making use of parameters that influence the occurrence of the psyllid previously tested by other authors (AURAMBOUT et al., 2009; CHIYAKA et al., 2012; TORRES-PACHECO et al., 2013; DIAZ-PADILHA et al., 2014; NAROUEI-KHANDAN et al., 2015; RAMIREZ et al., 2016), or simulate the occurrence of the psyllid in the laboratory (TAYLOR et al., 2019). This information helps in the construction of the models and is of great value to guide the modeling of occurrence of the psyllid. However, in the field the insects interact with several other factors, such as soil, crop, and management in addition to the climate. The model presented here to determine psyllid occurrence risk for the states of São Paulo, Florida, Texas, and California tried to cover all these factors. In addition, this study presented a comprehensive database, in terms of space and time, of the psyllid captures in orange orchards, which allowed evaluating different places and periods, based on a well calibrated and validated model. With this, the information generated in the present study can be used to determine the scape areas for HLB as well as help in the planning of the strategies for psyllid control in commercial orchards in Brazil and USA.

3.5. Conclusions

This study allowed to generate psyllid occurrence risk maps that can assist growers and consultants in the HLB vector control planning as well as in decision making for a more rational strategy for HLB management by identifying the months with the highest risk for psyllid occurrence.

The average annual risk for psyllid occurrence was greater in Florida than in the states of São Paulo, Texas and California. Those risks in the American states, Florida, Texas and California, showed to be higher in the south, whereas for the state of São Paulo, Brazil, the risks were higher in the northern region of the state.

Over the months, in the states of the United States of America, the risks of psyllid occurrence start to increase in late spring and reach its peak in summer months, from March to October, decreasing then until the winter. For the state of São Paulo, the psyllid occurrence has the risks increasing from spring, with the peak occurring in the summer, from October to January, decreasing gradually after that, with lower values occurring in the winter.

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4. AGROMETEOROLOGICAL MODELING AND CLIMATIC RISK OF CITRUS HUANGLONGBING (HLB)

ABSTRACT

Huanglongbing (HLB) is a disease caused by a bacterium that develops in the citrus phloem vessels and which has the psyllid as a transmitting agent. As HLB is a vascular disease, it affects the plant development, leading to a gradually yield reduction, and after some year to trees eradication. Due to these consequences, it is currently the main citrus disease around the world and mainly in Brazil, the one of the largest producers of orange juice, causing expressive losses for growers. This disease is mainly caused by the favorable weather conditions that control psyllid development and citrus sprouts, since this insect prefers new tissues. Considering the impacts of HLB for global citrus production and that this disease is influenced by weather conditions, the objectives of this study were to develop an agrometeorological model to estimate the number of plants drastically affected by the HLB, requiring eradication, and to determine the climatic risk for HLB occurrence in the state of São Paulo, Brazil. For this purpose, data of number of eradicated plants from eight farms in the state of São Paulo, covering the years 2010 to 2018, were used, five of which were used for model calibration and three for validation. To compare the different block sizes, the total number of plants eradicated per block was divided by the total number of plants in the block, to standardize the eradication and relativize it. The HLB occurrence model was based on the relationship between the occurrences of the psyllid, combined with different temperature thresholds that affect the development of the bacteria. The meteorological data used in this study comprised minimum, average, and maximum air temperature, relative humidity, rainfall, wind speed and solar radiation, for the same period when trees´ eradications were computed. The meteorological variables and the occurrence of the psyllid were correlated with the relative eradication, being evaluated on a monthly scale, and 3, 6, 12 and 18 months before eradication, and the best fit was chosen. After that, the most favorable temperature equation was obtained, combined with the occurrence of the psyllid, with different percentages being attributed until obtaining the greatest accuracy when comparing the estimated and observed eradication data. To evaluate the model, five levels of control were used in which the contingency table was evaluated. With the best fit of the model, the risk of occurrence of HLB was calculated for the state of São Paulo, on annual and monthly scales. For this, Xavier's database from 1981 to 2015 was used to obtain the 97 points, 70% of which were used to calibrate the map and 30% to validate the map. The maps were generated by the multiple regression method, which correlates the independent variable with latitude, longitude, and altitude. The following statistical indices and errors were used to evaluate the maps: correlation coefficient, Willmott's agreement index, Camargo and Sentelhas confidence index, Average Error, Absolute Mean Error, Absolute Mean Percentage Error, and percentage of correctness. The eradication model was based on 75% of monthly psyllid captures per block per month and 25% on the number of days favorable to the development of the bacteria, being tested the number of days per month with average daily temperatures below 22, 23, 24 and 25 °C. The psyllid model refers to the estimated value "n" months before eradication, whereas the temperature corresponds to that which occurred in the month of eradication. The temperature that obtained the best fit was 23 °C, with the best accuracy and the lowest number of false negatives in the five control levels tested. The annual risk of HLB is higher in the center and south and lower in the north of the state and the same is observed on the monthly scale.

Keywords: *Candidatus Liberibacter asiaticus*, Meteorological variables, Psyllid Occurrence, Disease Modeling.

4.1. Introduction

The citrus crop stands out in Brazil as an important export product, which increased in 2017/2018 growing season in comparison to 2016/2017 (CITRUSBR, 2018), being about 75% of the national production obtained in the state of São Paulo (IBGE, 2021). Despite the importance of this crop for the commercial balance of the country and the good climatic conditions that citrus faces in the state of São Paulo, the production has been highly affected by phytosanitary problems, since several pathogens attack the citrus plants. Nowadays, the main citrus disease is the huanglongbing (HLB), which can affect 80% of the orchard if not properly controlled (BASSANEZI et al., 2013). According to the same authors, if the disease management occurs at the farm level, it can be reduced to 50%, and when adopting regional management, the proportion of HLB can fall to 6% or even less if, regional and local management measures are combined. According to a survey conducted by Fundecitrus (Citrus Defense Fund), in 2018 there was an increase in the incidence of HLB compared to the previous year, and the current level of the disease is the highest since 2004 (FUNDECITRUS, 2018), when HLB was firstly detected in the country (COLETTA-FILHO et al., 2004)

HLB is a disease caused by the bacterium whose species are: *Candidatus* Liberibacter africanus; *Candidatus* Liberibacter asiaticus; and *Candidatus* Liberibacter americanus (BOVÉ, 2006), with the latter two being reported in the country (GASPAROTO et al., 2012). However, the highest currently proportions of the disease in Brazil are related to *Ca.* L. asiaticus (LOPES et al., 2009). The disease transmission occurs through a psyllid vectors: *Diaphorina citri* (GALLO, GALLO, 2002) and *Trioza erytreae* (MCCLEAN; OBERHOLZER, 1965), with only the first one occurring in Brazil (PARRA et al., 2010). The plants infected by the bacteria have the following symptoms: yellowish colored leaves; leaf fall; smaller branches; fruits with yellowish spots and asymmetrical format; deformed and sterile seed; and having premature fruits fall. Moreover, the plants that are infected by the bacteria become unproductive in a few years, being necessary to eradicate them, which raises the production costs (BOVÉ, 2006; BOSCARIOL-CAMARGO et al., 2010).

Regarding the climate of the main citrus producing regions in Brazil, it is favorable for the crop, since citrus plants can develop over a wide range of temperatures, from 12 to 31 °C, tolerating up to 37 °C (REUTHER, 1973). Such behavior justifies the production of citrus from the south to the north of Brazil (IBGE, 2021). When considering the soil water availability, this can change citrus phenology, since plants´ sprouting occurs in a more concentrated way when an intense water deficiency is followed by a precipitation of at least 20 mm. The plants´ sprouting in citrus orchards promotes a growth of the vector population, since it favors the oviposition

(PARRA et al., 2010), with the young insects having preference by the new branches, while the adults, even preferring the new branches, also attack the older ones (DINIZ, 2013).

The control of the vector, which is the main mechanism of management of the disease, is a difficult task since it has two forms of dispersal, primary and secondary (BASSANEZI et al., 2010; BERGAMIN FILHO et al., 2016). According to the cited authors, the primary one is that which occurs from between properties, while the secondary is that which occurs within the property, through the infection caused by the psyllid when migrating from one plant to another. Primary dispersal depends on the control outside the property (regional), and if it does not occur, it will result in constant infections on the farm (local). Secondary dispersal is easier to control since it depends on local management, but less effective when the regional control does not occur.

In addition to the increase in control activities, HLB has increased production costs (BELASQUE JUNIOR et al., 2009) once it requires plants eradication when the disease level is too high. Regarding plant eradication, from 2004 to 2014, it is estimated that more than 40 million plants with HLB symptoms were eliminated only in the state of São Paulo and in the west of the state of Minas Gerais (Triângulo Mineiro) (NEVES et al., 2010), without considered the orchards with symptoms in the state of Paraná and other regions of Minas Gerais (BELASQUE JUNIOR et al., 2009). In the USA, both citrus area and production declined in 2017 because of HLB, especially in Florida, the main producing state (USDA, 2020).

HLB represents a disease of great importance for the citrus both at a national and worldwide level, causing negative impacts on productivity and production costs of the orchards, since the eradication of plants and the use of insecticides for controlling the vector, both inside and outside the orchards, have increased substantially. Considering that, it is of major importance to know the climatic conditions that favor the vector and the disease in order to better control the development and dispersion of the vector and, consequently, of HLB, making possible to identify the areas of higher risk of disease occurrence, both at regional and local level, and to establish more rational control strategies. The present study hypothesis was that the meteorological conditions affect the development and dispersion of the HLB vector and that is possible to establish the areas of highest risk, based on tree´s eradication data, as well as the seasons of the year that have the highest occurrence for the disease to improve the decision making for a most effective disease control. Therefore, the objectives of this study were to develop an agrometeorological model to estimate the number of plants drastically affected by the HLB, requiring eradication, and to determine the climatic risk for HLB occurrence in the state of São Paulo, Brazil.

4.2. Material and methods

4.2.1. Eradication of HLB symptomatic trees

Data on trees eradication with symptoms of HLB were obtained from eight farms located in the state of São Paulo in the central and central-northern regions of the state, which comprised a period from 2010 to 2018 (Figure 1). The data on eradicated plants underwent a consistency analysis in which they were converted into relative eradication per block, this was done through the number of plants eradicated per block in relation to the total number of plants per block. This was done because the number of plants per block is quite variable among the farms, and the assessment of total eradication is also different when comparing larger and smaller blocks, so when relativizing eradication, this aspect is minimized.

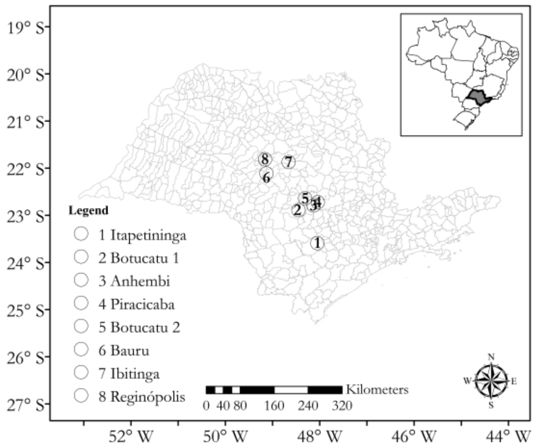

Figure 1. Location of the eight farms in the state of São Paulo, Brazil, where data of citrus tree eradications came from.

4.2.2. Meteorological data

Daily meteorological data from the database of Xavier et al. (2016) and CHIRPS (2018) (Climate Hazards Group InfraRed Precipitation with Station data) were employed for the modeling eradication process. These databases were used together with observed weather data from the closest stations of the National Institute of Meteorology (INMET), resulting in complete series for all assessed locations. These meteorological databases were submitted to a consistency analysis in order to check for possible gaps and errors. The meteorological variable considered were: maximum and minimum air temperature; relative humidity; rainfall; and wind speed.

4.2.3. HLB estimation model

The HLB detection model was based on the agrometeorological model for estimating the number of psyllids per block. However, according to Lopes et al. (2009), Folimonova and Achor (2010) Canale et al. (2016) and Hilf and Lewis (2016), the occurrence of the psyllid only does not guarantee the occurrence of HLB, as its transmission is variable and depending also on favorable conditions for the bacteria. Based on that and considering that the symptoms of HLB appear six to eighteen months after infection (BOVÉ, 2006), temperature for these periods were also considered in disease modeling process. Therefore, temperature conditions that are related to the development of bacteria, the causal agent of HLB, were also evaluated, considering the thresholds presented by Gasparoto et al. (2012) and Lopes et al. (2009) (Table 1). In addition, the methodology described by Jesus Junior et al. (2008) for Citrus Variegated Chlorosis (CVC), which showed greater detection of the disease-causing bacteria in conditions of greater water deficit, was also considered in the model (Table 1).

4.2.4. Data analysis

To model the citrus trees eradication, the relative monthly eradication was correlated with the weather variables (Table 1) and, also, with the number of psyllids captured per block, estimated by the agrometeorological model, described in Chapter 2, both on a monthly scale, considering the incubation period. These variables were analyzed on the monthly scales, as well as considering the periods of 1, 3, 6, 12 and 18 months before the eradication date. After the best correlation was found, the eradication model was built, and then different percentages were assigned to the trees´ eradication and detection model (Figure 2). At first, the model was calibrated with 2/3 of the observed data on the eradication of plants with symptoms of HLB. This step was performed to verify whether the model estimates the detection of the disease well over time, compared to the observed data. After that, the model was validated with 1/3 of the observed data on the eradication of diseased plants, and these data are independent, that is, they were not part of the calibration. This step was performed to verify if the models estimate the detection of HLB properly.

Table 1. Meteorological variables tested in the modeling of the detection of trees eradication caused by HLB in citrus.

Variables*	Reference**
Tavg < 27 °C	Gasparoto et al. (2012); Lopes et al. (2009)
Tmax < 27 °C	Gasparoto et al. (2012); Lopes et al. (2009)
Tavg < 32 °C	Lopes et al. (2009)
Tmax < 32 °C	Lopes et al. (2009)
Tavg < 26 °C	Gasparoto et al. (2012); Lopes et al. (2009)
Tmax < 26 °C	Gasparoto et al. (2012); Lopes et al. (2009)
Tavg < 25 °C	Gasparoto et al. (2012); Lopes et al. (2009)
Tmax < 25 °C	Gasparoto et al. (2012); Lopes et al. (2009)
Tavg < 24 °C	Gasparoto et al. (2012); Lopes et al. (2009)
Tmax < 24 °C	Gasparoto et al. (2012); Lopes et al. (2009)
Tavg < 23 °C	Gasparoto et al. (2012)
Tmax < 23 °C	Gasparoto et al. (2012)
Tavg < 22 °C	Gasparoto et al. (2012)
Tmax < 22 °C	Gasparoto et al. (2012)
Tavg > 22°C e Tmax < 32 °C	Gasparoto et al. (2012); Lopes et al. (2009)
# days with WD	Jesus Junior et al. (2008)
Total WD	Jesus Junior et al. (2008)
WD ≥ 5 mm in 7days	Jesus Junior et al. (2008)
WD ≥ 10 mm in 7days	Jesus Junior et al. (2008)
WD ≥ 15 mm in 7 days	Jesus Junior et al. (2008)
WD ≥ 15 mm in 30 days	Jesus Junior et al. (2008)
WD ≥ 20 mm in 30 days	Jesus Junior et al. (2008)
Tmax < 27 °C and WD ≥ 10 mm	Gasparoto et al. (2012); Lopes et al. (2009); Jesus Junior et al. (2008)
Tavg > 22 °C and Tmax < 35°C	Gasparoto et al. (2012); Lopes et al. (2009)
Tavg > 22 °C, Tmax < 35°C and WD ≥ 10 mm	Gasparoto et al. (2012); Lopes et al. (2009); Jesus Junior et al. (2008)
Tmax < 35 °C	Lopes et al. (2009)
Tavg < 35 °C and WD ≥ 10 mm	Lopes et al. (2009); Jesus Junior et al. (2008)
# days with R	Jesus Junior et al. (2008)
Total R	Jesus Junior et al. (2008)
Tavg > 22 °C, Tmax < 35°C and R ≥ 20mm	Gasparoto et al. (2012); Lopes et al. (2009)
R < 1mm	Jesus Junior et al. (2008)
Tavg > 22 °C, Tmax < 35°C, WD ≥ 10 mm and R < 20 mm	Gasparoto et al. (2012); Lopes et al. (2009)
# days with R ≥ 20 mm	Jesus Junior et al. (2008)
Tavg > 22 °C, Tmax < 35°C and R = 0 mm	Gasparoto et al. (2012); Lopes et al. (2009)
Tavg > 22 °C, Tmax < 35°C, R = 0 mm and WD ≥ 10 mm	Gasparoto et al. (2012); Lopes et al. (2009)

* Tavg = average air temperature; Tmax = maximum air temperature; R = rainfall; WD = water deficit; # = number of.

**Weather and weather-derived variables adapted from the literature.

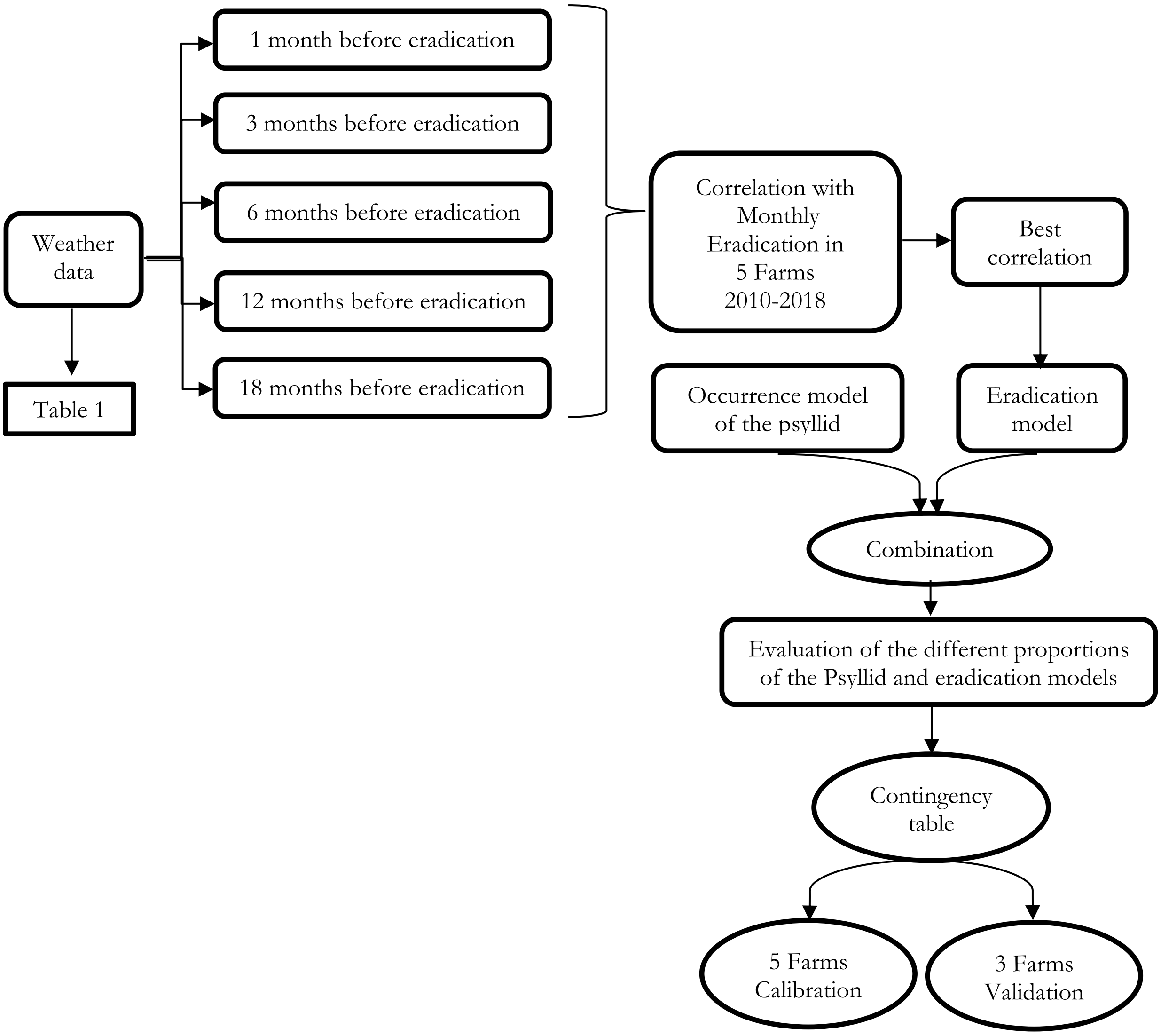

Figure 2. Flowchart of the procedures for modeling trees eradication in citrus orchards.

For the evaluation of the best model of trees eradication caused by HLB in the calibration phases, the contingency table was used, evaluating the number of correct non-eradications and eradications, as well as errors in eradicating the trees when it is not necessary or not eradicating when it should be eradicated (Table 2). To define the levels used in the contingency table (KIM et al., 2010), the results were divided into five levels using values that contained about 20% of the data observed at each one of them (Figure 3).

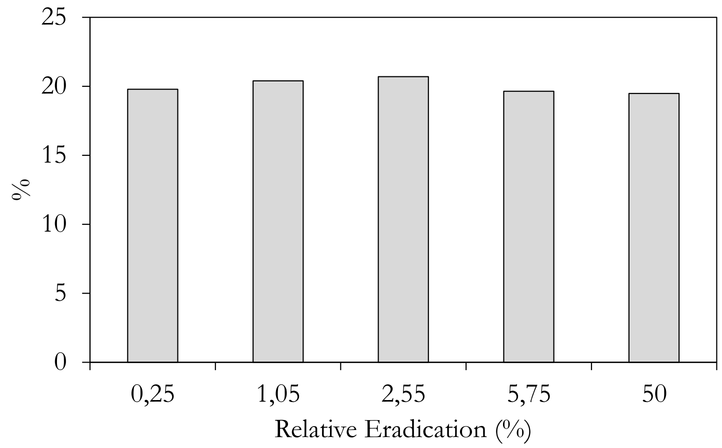

Figure 3. Five classes of relative trees eradication in citrus orchards and their respective percentages.

Table 2. Contingency table used to evaluate the best fitted model for estimating the number of relative trees eradication in citrus orchards.

	Estimated (Above or equal)	**Estimated (Below)**
Observed (Above or equal)	Correct positive (X)	False negative (Y)
Observed (Below)	False positive (W)	Correct negative (Z)

X and Z denote correctness of the model, with X representing that estimated number of eradications is above or equal the given threshold and it agrees with the observed data, and Z when the estimated number of eradications is below the given threshold and it agrees with the observed data. Y and W denote errors in the model, with W representing that estimated number of eradications is above or equal the given threshold while the observed number is below of that, and Y when the estimated number of eradications is below the given threshold while the observed number is above or equal of that.

To evaluate the eradication model, the fraction of correct estimates (Fc) was used, which represents the sum of the number of correct negatives (Z) and positives (X) (Table 2) divided by the total number of correct answers (X + Z) and errors (Y + W), with results varying from 0 to 1, with 0 indicating that the model is unable to predict the number of eradications, and 1 that the model correctly represents eradications (KIM et al., 2010). Equation 2.4.1 represents the calculation of Fc:

$$F_C = \frac{X+Z}{X+Y+W+Z} \quad (1)$$

To calculate the correct positive (C_P), correct negative (C_N), false positive (F_P) and false negative (F_N) fractions, the number of each of these factors was divided by the total number of hits and errors in the eradication model. For the calculation of the bias (Bs), the relationship between the estimates above the limit of the observed values, both correct (X) and incorrect (W), and the values observed above a certain level, also counting the correct (X) and incorrect (Y) values was considered, as presented below. The Bias expresses the model's tendency if it is underestimated (<1), overestimated (> 1) or has no tendency (= 1).

$$B_S = \frac{X+W}{X+Y} \tag{2.}$$

Figure 4 shows the details of the procedures considered in the citrus trees eradication model. At first, the number of days per month with average temperature below 22, 23, 24 and 25 °C was counted and then accumulated for the periods of 1, 3, 6, 12 and 18 months before the month of eradication. The accumulated days with average temperature below the specific threshold for the different periods were then correlated with the number of relative eradications in the farms. Once adjusted, the model of citrus tree eradications was combined with the model of the occurrence of psyllids per block. For the estimation of the detection of HLB symptomatic plants the favorable temperature to the bacteria had a weight of 25%, whereas for the occurrence of the psyllid the weight was 75%. The population of psyllids was estimated for the month in the beginning of the period considered for bacteria development, which was 1, 3, 6, 12 and 18 months before eradication calculation, whereas the temperature for the bacteria development was considered in the 30 days that proceeded the month of eradication.

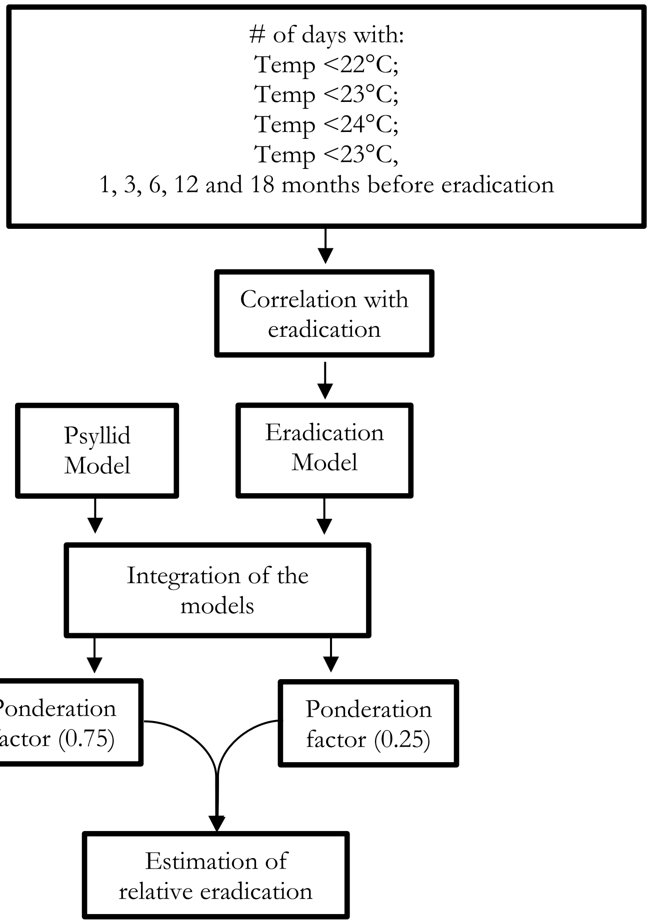

Figure 4. Flowchart of the model for estimating citrus tree eradications, based on the number of psyllids captured per block, according to the agrometeorological model, and on the correlation between trees eradications and temperature below a given threshold.

To check the sensitivity of the model presented in Figure 4, variations were made in the meteorological input data of the models for estimating citrus tree eradication, with HLB symptom, to verify how it responds to increase and decrease in average air temperature of 2 °C.

4.2.5. Risk of citrus tree eradication

To obtain the risk of eradication of citrus trees with HLB symptoms, gridded meteorological database of Xavier et al. (2016), from 1981 to 2015, was used to estimate eradications. The number of locations used for risk assessment was 97, which were used to calibrate (70%) and validate (30%) the multiple linear model which was used to spatialize the eradication risk. The calibration comprised the adjustment of the multiple linear models by correlating estimated number citrus trees eradications with latitude, longitude, and altitude, whereas the validation was performed by comparing the eradications simulated by the linear model with those obtained by the agrometeorological models (psyllid occurrence and bacteria favorability).

Figure 5 shows the scheme used to calculate the risk of relative eradication (RErad) for the State of São Paulo. For that, multiple linear models were adjusted to estimate the number of days in the month with air temperature favorable to bacterium development - #DTFB (Equation 3) and the number of psyllids captured per block per month – NPBM (Equation 4), both as function of latitude (lat, in decimal degrees), longitude (long, in decimal degrees), and altitude (alt, in m). After these estimations, the RErad was calculated by weighting these two variables (Equation 5):

$$\#DTFB = a + b \times Lat + c \times Long + d \times Alt \tag{3}$$

$$NPBM = a + b \times Lat + c \times Long + d \times Alt + e \times Lat^2 + f \times Long^2 + g \times Alt^2 + h \times Lat \times Long + i \times Lat \times Alt + j \times Long \times Alt \tag{4}$$

$$RErad = 0.25 \times \#DTFB + 0.75 \times NPBM \tag{5}$$

Finally, the equation for estimating RErad was applied to obtain the risk map for the detection of HLB, which was classified into five classes (Very low; Low; Medium; High; and Very High), according to the Tables 3 and 4 show the ranges used for risks based on RErad, for stablishing the classes of risk for the states of São Paulo, respectively for the monthly and annual time scales along the historical series assessed (1981-2015).

Table 3. Classes of climate-based risk levels of relative eradication as a function of the number of psyllid (NPBM),the number of psyllid generations (NPG) and its combination with the air temperature favorable to bacterium development (DTFB) for the annual time scale.

Risk	Risk based on NPBM*NPG	Risk based on DTFB*NPBM*NPG
Very Low (1)	≤463	≤0.6
Low (2)	463.01-746	0.601-0.7
Medium (3)	746.01-1009	0.701-0.8
High (4)	1009.01-1272	0.801-0.9
Very High (5)	>1272	>0.9

Table 4. Classes of climate-based risk levels of relative eradication as a function of the number of psyllid (NPBM),the number of psyllid generations (NPG)and its combination with the air temperature favorable to bacterium development (DTFB) for the monthly time scale.

Risk	Risk based on NPBM*NPG	Risk based on DTFB*NPBM*NPG
Very Low (1)	≤1704	≤0.6
Low (2)	1704.01-3408	0.601-0.7
Medium (3)	3408.01-5112	0.701-0.8
High (4)	5112.01-6816	0.801-0.9
Very High (5)	>6816	>0.9

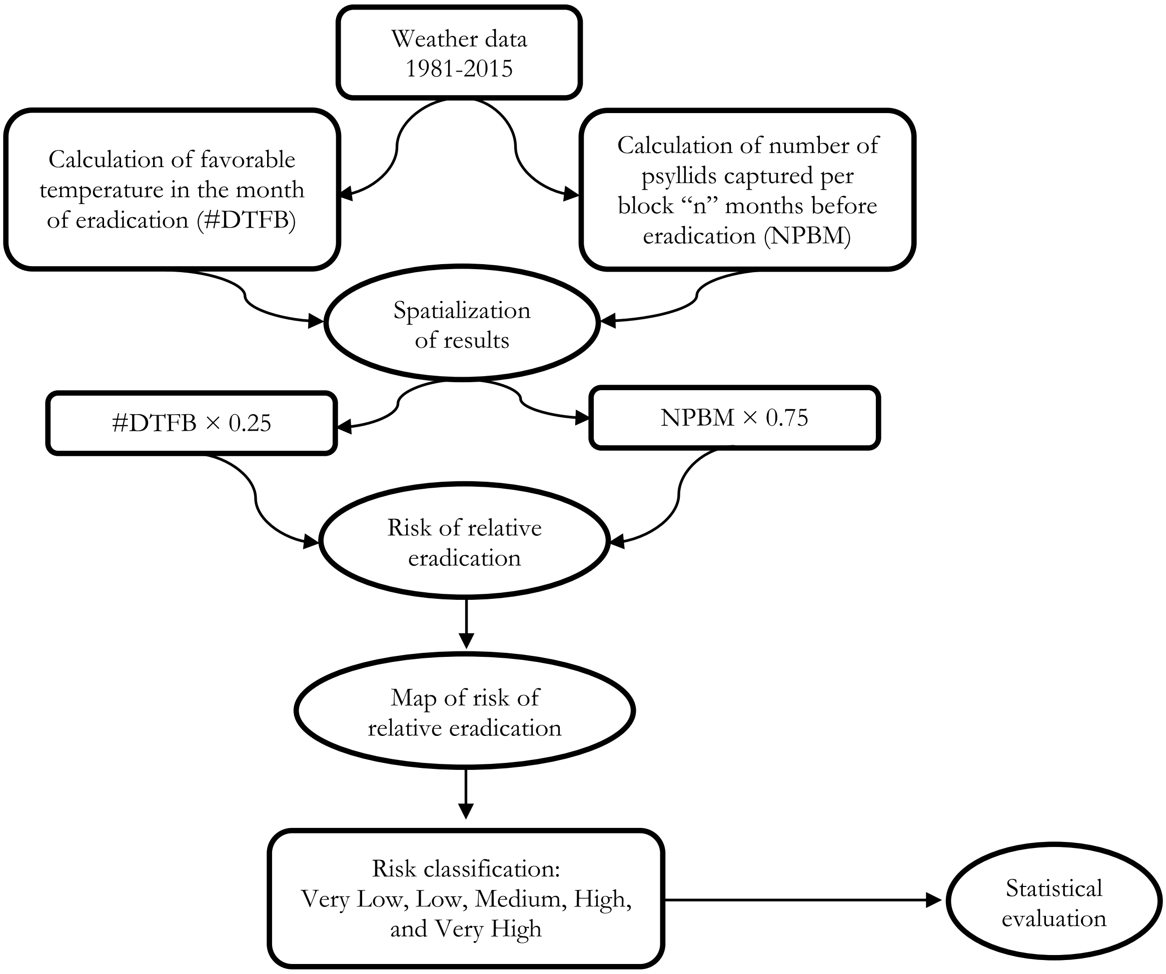

Figure 5. Flowchart of risk of relative eradication determination, based on the number of days in the month with air temperature favorable to bacterium development (#DTFB) and the number of psyllids captured per block per month (NPBM).

The maps of these two variables (#DTFB and NPBM) were prepared through the multiple linear regression methods. This method uses the correlation of the dependent variables (#DTFB and NPBM) with latitude, longitude and altitude, since they depend on the climatic conditions, which in run depend on the geographic coordinates and elevation of the region. Both maps were then employed to estimate RErad by using map algebra in the ArcGis 10.6.1 Software (ESRI) for pixel resolution of 90 x 90 m.

The evaluation of the maps was done by comparing the risks of RErad estimated by the multiple linear model and calculated with the agrometeorological models. For the statistical analysis, the following indices and errors were used: correlation coefficient (*r*); Willmott's agreement index (*d*); Camargo and Sentelhas (1977) confidence index (*c*); mean error (ME); Mean Absolute Error (MAE); Mean Absolute Percentage Error (MAPE); and the fraction of correct estimates from the contigency table.

4.3. Results

4.3.1. Models for estimating the citrus tree relative eradication

The equations 6 to 9 are the models for estimating the relative eradication of citrus trees with HLB symptoms (RErad), based on the eradication data from the assessed farms. These models differ in terms of the total number of days with average temperature below 22, 23, 24 and 25 °C in the month of eradication (#DTFB_Txx), since for the other independent variable, number of psyllids captured per block per month in the moment of bacterium transmission, the period used between transmission and symptoms detection was of 18 months (NPBM18). For the occurrence of HLB, incubation periods were evaluated, with intervals of 1, 3, 6 and 12 months showing the poorest results. The first variable had a weight of 75% and the second 25% in the final RErad, as presented below:

$$RErad\_T22 = 0.0005 * (NPBM18 * 0.75) + 0.0133 * (\#DTFB\_T22 * 0.25) - 0.001 \quad (6)$$
$$RErad\_T23 = 0.0005 * (NPBM18 * 0.75) + 0.0095 * (\#DTFB\_T23 * 0.25) - 0.002 \quad (7)$$
$$RErad\_T24 = 0.0005 * (NPBM18 * 0.75) + 0.0121 * (\#DTFB\_T24 * 0.25) - 0.008 \quad (8)$$
$$RErad\_T25 = 0.0005 * (NPBM18 * 0.75) + 0.0122 * (\#DTFB\_T25 * 0.25) - 0.015 \quad (9)$$

4.3.2. Evaluation of the models for estimating the citrus tree relative eradication in the state of São Paulo

Figure 6 shows the comparison of RErad estimated by the four models (Equations 6 to 9) and the observed data obtained in the farms in the state of São Paulo. The results showed a huge variability, with estimated RErad presenting, in general, lower variability than observed in the field for both calibration and validation phases and for the different temperatures tested. Whereas for estimated RErad the maximum values reached 30%, in the field the farmers reported till 41%. However, when the proportion of eradication limits were considered, the results in terms of correctness change expressively, as presented in Table 5.

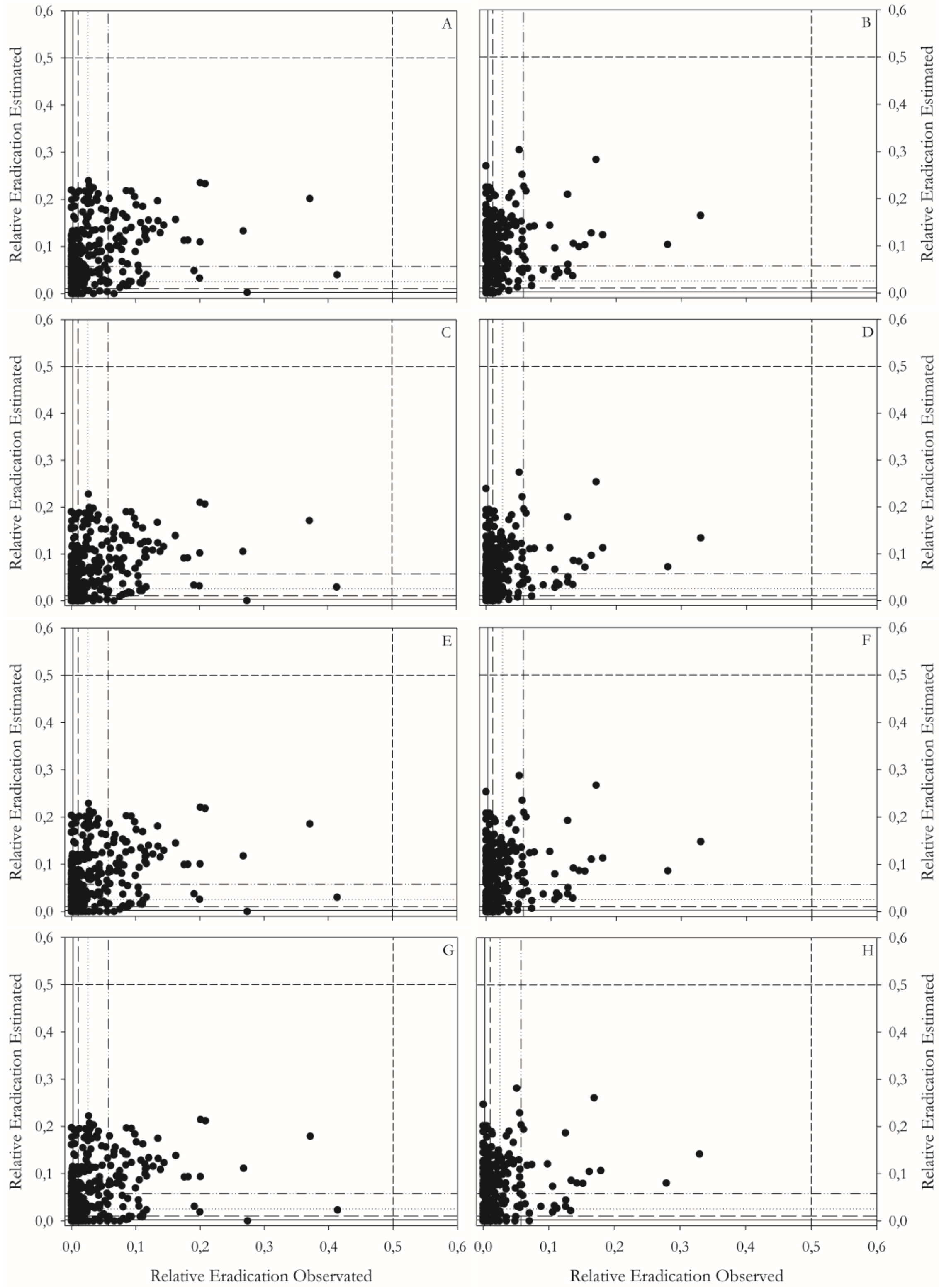

Figure 6. Relationship between observed and estimated relative eradications of citrus trees with HLB symptoms, during the models calibration (A, C, E and G) and validation (B, D, F and H), considering the following temperatures thresholds for the variable total number of days with average temperature below a given value (#DTFB_Txx): 22 °C (A and B); 23 °C (C and D); 24 °C (E and F); and 25 °C (G and H), for the five proportion limits considered (0.0025; 0.0105; 0.0255; 0.0575; and 0.5). The lines indicate the five eradication levels tested.

Table 5 shows the statistical evaluation of the four models for estimating the relative eradication of citrus trees with symptoms of HLB (RErad). In all models there is an oscillation of the values of false negatives and fraction of correct estimate, and, in general, there is a decrease in the fraction of correct estimate and an increase in the false negatives as the control threshold increases and improves again at the last limits The model with the lowest false negatives and fraction of correct estimate (F_C) values at all eradication limits was RErad_T23. Supplementary material 1 at the end of this chapter, contains a statistical evaluation comparing correct positives, correct negative, and accuracy.

Model RErad_T22 has better accuracy in calibration compared to validation (Table 5), but the number of false negatives is higher in the first. The variation in the estimated eradication value is from 0 to 0.25 (Figure 6A) in the calibration, whereas for the observed data it is from 0 to 0.41 (Figure 6A). In the validation, however, it ranges from 0 to 0.3 in the estimated data (Figure 6B) and in the observed data from 0 to 0.35 (Figure 6B). The worst hit of the model occurs at the control level (CL) of 0.0575 of relative eradication, but false negatives are still low.

Model RErad_T23 has a slightly higher accuracy than RErad_T22 at some levels of control, and in addition, the false negative is lower in this model (Table 5). Regarding the variation of the estimated and observed values, RErad_T23 (Figures 6C and 6D) was similar to RErad_T22 (Figures 6A and 6B). For RErad_T23, the smallest hit also occurs for the limit of eradication of 0.0575.

Models RErad_T24 and RErad_T25 presented similar results and have the lowest false negative values, however, their hit values were lower at the control limits of 0.0255 and 0.0575 (Table 5). The variations of the values observed in the calibration and validation phases are similar for both models (Figure 6E, 6F, 6G and 6H), which was almost the same as observed for RErad_T22 (Figure 6A and 6B).

Table 5. Performance of the models for estimating the relative eradication of citrus trees with HLB symptoms, during the calibration (Cal.) and validation (Val.) phases for five limits eradication in the state of São Paulo, Brazil: RErad_T22 – model considering number of days with temperature less than 22 °C; RErad_T23 – model considering number of days with temperature less than 23 °C; RErad_T24 – model considering number of days with temperature less than 24 °C; RErad_T25 – model considering number of days with temperature less than 25 °C.

	RErad_T22		RErad_T23		RErad_T24		RErad_T25	
Indices*	**Cal.**	**Val.**	**Cal.**	**Val.**	**Cal.**	**Val.**	**Cal.**	**Val.**
Limit of 0.0025 of Relative Eradication								
C_N	0.049	0.036	0.036	0.020	0.022	0.016	0.014	0.004
F_P	0.173	0.238	0.187	0.254	0.201	0.258	0.209	0.270
F_N	0.066	0.052	0.044	0.028	0.019	0.016	0.011	0.000
C_P	0.712	0.675	0.734	0.698	0.758	0.710	0.766	0.726
F_C	76%	71%	77%	72%	78%	73%	78%	73%
B_S	0.519	0.319	0.358	0.174	0.185	0.116	0.111	0.014
Limit of 0.0105 of Relative Eradication								
C_N	0.107	0.079	0.091	0.067	0.066	0.040	0.030	0.024
F_P	0.286	0.429	0.302	0.440	0.327	0.468	0.363	0.484
F_N	0.063	0.044	0.044	0.024	0.025	0.012	0.016	0.008
C_P	0.544	0.448	0.563	0.468	0.582	0.480	0.591	0.484
F_C	65%	53%	65%	54%	65%	52%	62%	51%
B_S	0.434	0.242	0.343	0.180	0.231	0.102	0.119	0.063
Limit of 0.0255 of Relative Eradication								
C_N	0.206	0.175	0.176	0.159	0.135	0.107	0.082	0.052
F_P	0.360	0.548	0.390	0.563	0.431	0.615	0.484	0.671
F_N	0.099	0.032	0.080	0.024	0.052	0.008	0.030	0.004
C_P	0.335	0.246	0.354	0.254	0.382	0.270	0.404	0.274
F_C	54%	42%	53%	41%	52%	38%	49%	33%
B_S	0.539	0.286	0.451	0.253	0.330	0.159	0.199	0.077
Limit of 0.0575 of Relative Eradication								
C_N	0.409	0.385	0.401	0.405	0.343	0.270	0.264	0.214
F_P	0.341	0.508	0.349	0.488	0.407	0.623	0.486	0.679
F_N	0.088	0.040	0.088	0.040	0.069	0.028	0.055	0.020
C_P	0.162	0.067	0.162	0.067	0.181	0.079	0.195	0.087
F_C	57%	45%	56%	47%	52%	35%	46%	30%
B_S	0.663	0.476	0.652	0.498	0.549	0.333	0.425	0.262
Limit of 0.5 of Relative Eradication								
C_N	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
F_P	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F_N	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C_P	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F_C	100%	100%	100%	100%	100%	100%	100%	100%
B_S	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

*C_N: Correct negative; F_P: False positive; F_N: False negative; C_P: Correct positive; F_C: Fraction of correct estimate and B_S: Bias.

The relative eradication observed in the eight farms in the state of São Paulo is quite variable, with the farm farther north, Reginópolis (8), showing greater eradications rate than Itapetininga (1), farm located in the south of the state of São Paulo. Also, in Itapetininga the interannual variability was lower than in Reginópolis. The other farms located in Anhembi (3), Piracicaba (4), Botucatu (2 and 5), Bauru (6) and Ibitinga (7) presented intermediary average values and variability (Figure 7A). When estimated relative eradications were considered (Figure 7B), the variability detected in the observed data was not reproduced by the model, with little differences among the farms (Figure 7B).

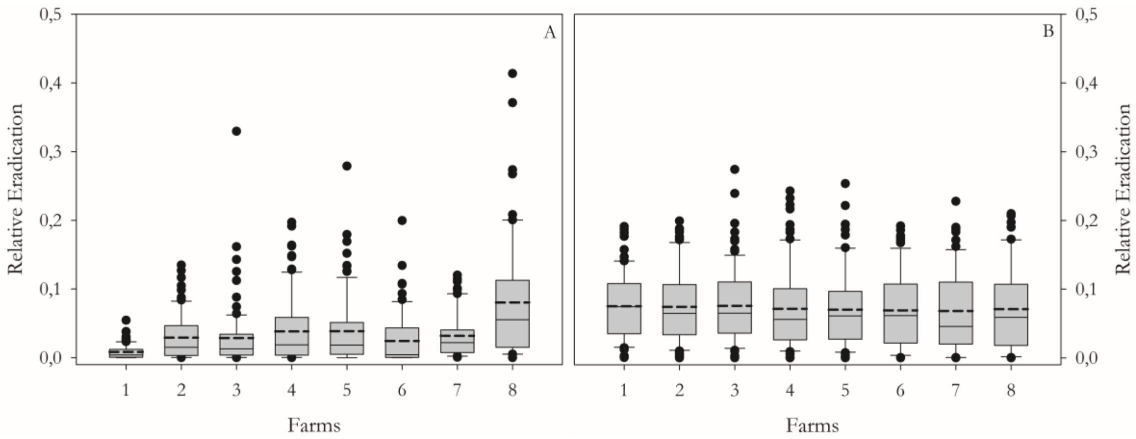

Figure 7. Relative eradications observed in the farms (A) and estimated by the model with number of days with temperature lower than 23 °C (B) in eight farms located in the state of São Paulo, Brazil: Itapetininga (1); Botucatu (2); Anhembi (3); Piracicaba (4); Botucatu (5); Bauru (6); Ibitinga (7); and Reginópolis (8). The dotted lines indicate the average.

The sensitivity analysis of the models for estimating relative eradication for two farms, one in the south and the other in the central north of the state of São Paulo is presented in Figure 8. For all levels of temperature, considered in the model for estimating de number of psyllids, the results varied slightly. In all cases, the temperature reduction of 2 °C resulted in an increase of the relative eradication, whereas higher temperatures (+ 2 °C) showed a decrease in relation to the present conditions and, also, in relation to the simulations with -2 °C. These results confirm the suitability of the model to estimate the relative eradication under different weather conditions.

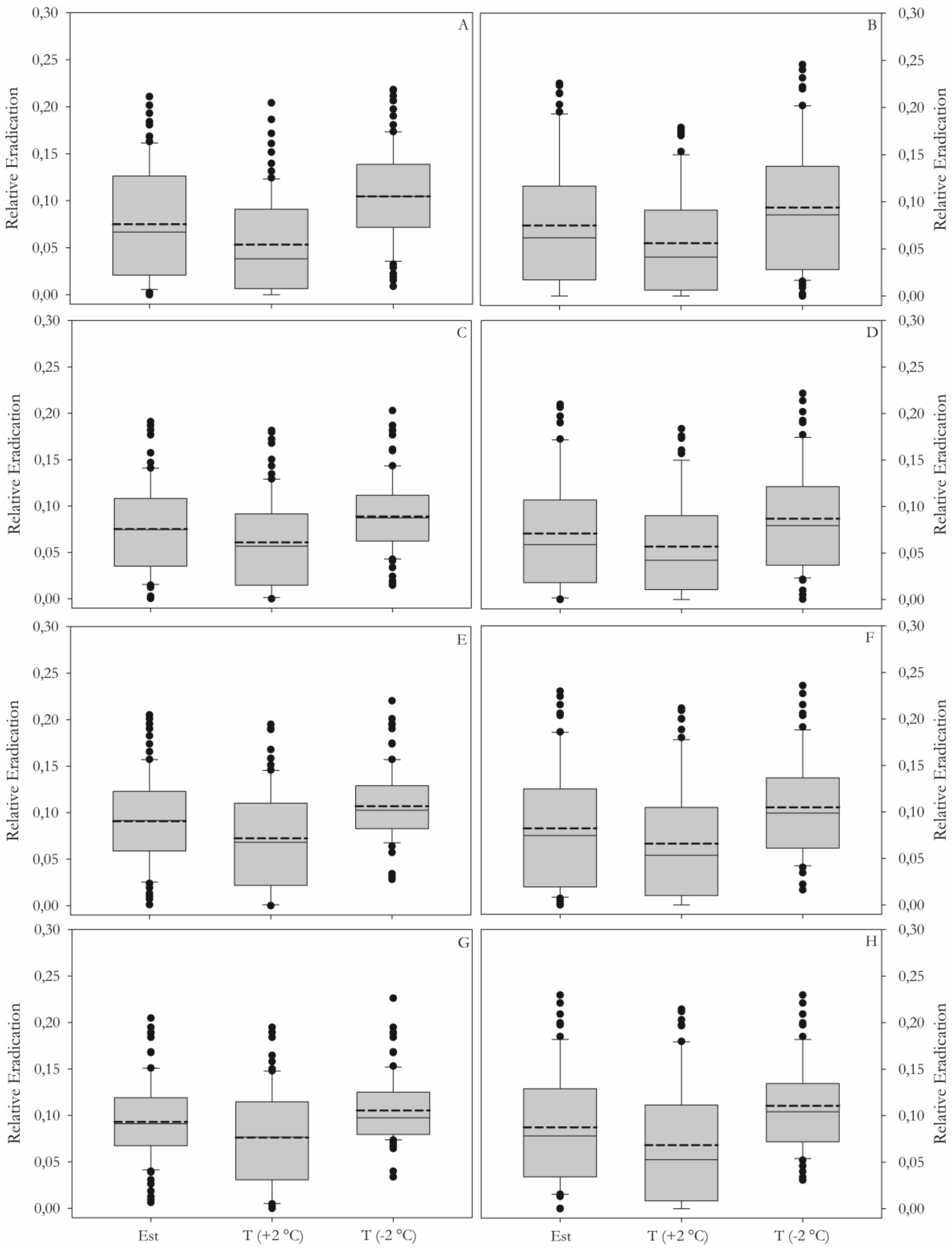

Figure 8. Sensitivity analysis of the models for estimating the relative eradication, based on the number of days with temperature lower than 22 °C (A and B), 23 °C (C and D), 24 °C (E and F), and 25 °C (G and H), for Itapetininga (A, C, E and G) and Reginópolis (B, D, F and H), state of São Paulo, Brazil, considering changes in air temperature (-2 °C and +2 °C). The dotted lines indicate the average.

4.3.3. Monthly assessment of relative eradication of citrus trees with symptoms of HLB in the state of São Paulo

Figure 9 presents the monthly variation of relative eradication of citrus trees with symptoms of HLB from 2010 to 2018 estimated by models (Figure 9A, 9B, 9C and 9D) and observed in the farms (Figure 9E).

As observed in Figure 9, the eradication occurs in all months of the year, but this is greater in the autumn and winter periods, both when estimated by the models (from April to September) and when observed in the orchards (from April to October). Although the estimated and observed values vary, the accuracy of the models was satisfactory at some limits of control, however, not so good for others (Table 5). All models presented a similar variation of estimated relative eradication mainly from autumn to winter, and differed more in the summer, when the eradication was slightly lower for the models that use the temperature thresholds of 22 and 23 °C.

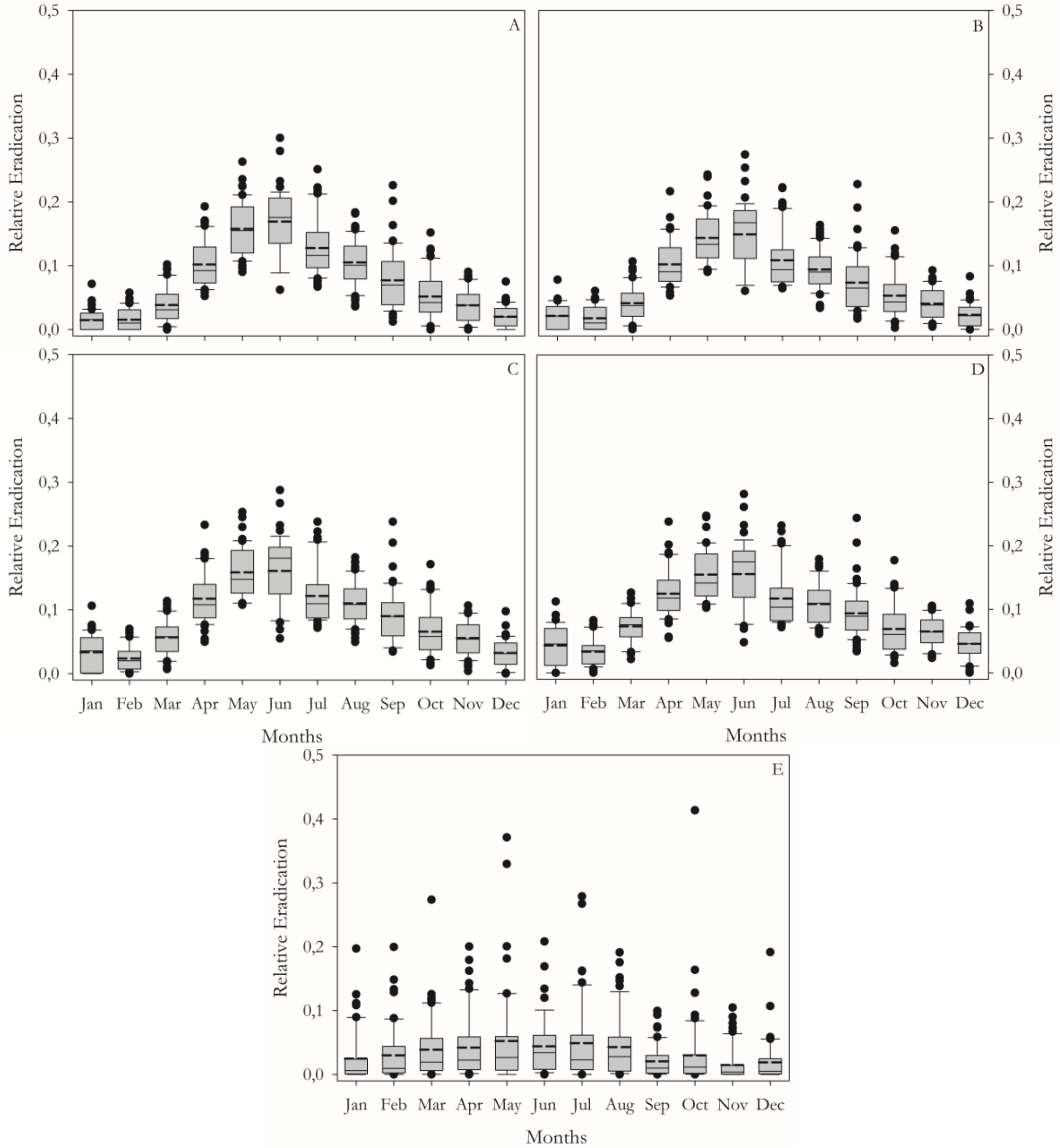

Figure 9. Monthly variability of relative eradication of citrus trees with HLB symptoms estimated by the model with different levels of temperature: 22 °C (A); 23 °C (B); 24 °C (C); 25 °C (D), and observed (E), in the eight farms assessed in the state of São Paulo, in the period from 2010 to 2018. The dotted lines indicate the average.

4.3.4. Annual risk of eradiation of citrus trees with HLB symptoms

Figure 10 shows the annual risk of eradiation of citrus trees with HLB symptoms for the state of São Paulo, which is low in the extreme north and northwest regions of the state, increasing towards the south when considering the main citrus producing regions of São Paulo. Most of the citrus areas of São Paulo is between medium, in the center-north, and high, in the center-south, risk for citrus trees eradication. It is a measure of how important is HLB for the citriculture of the state of São Paulo and why it is one of the most dangerous disease for this crop. The multiple linear regression models used to generate this map are presented in the Appendices F1.1 and F1.2.

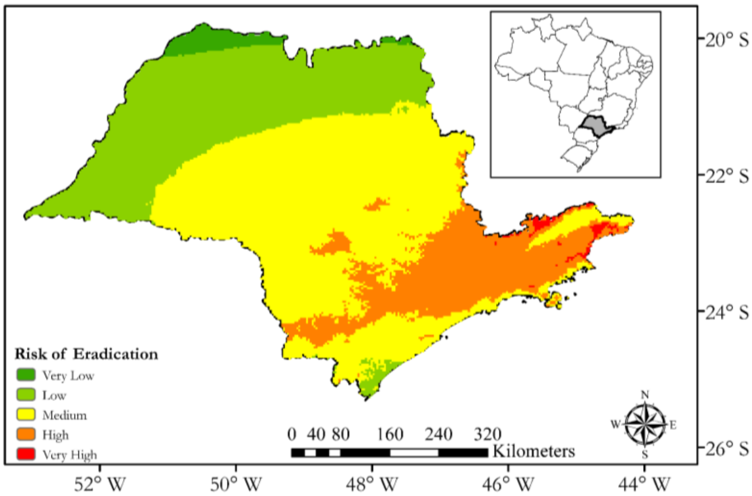

Figure 10. Annual risk of eradiation of citrus trees with HLB symptoms in the state of São Paulo, Brazil.

For the evaluation of the map of annual relative eradication risk presented in Figure 10, independent data were employed to assess the performance of the two variables (NPBM18; #DTFB_T23) that composed the final model (Table 6). The results of this analysis show the NPBM18 presented high precision ($r \geq 0.80$), high accuracy ($d \geq 0.88$) and a high confidence ($c \geq 0.70$), resulting in relatively small errors with hit that varies from 76% to 79%. Considering that, the number DTFB_T23, it was: $r \geq 0.94$; $d \geq 0.96$; and $c \geq 0.90$.

Table 6. Performance of the models for estimating the number of psyllid per block per month 18 months before the eradication (NPBM18) and the number of days with average temperature below 23 °C in the month of eradication (#DTFB_T23), used to calculate the annual risk of eradication of citrus trees with HLB symptoms, considering the correlation coefficient (*r*), Willmott agreement index (*d*), Camargo and Sentelhas confidence coefficient (*c*), mean error (ME), mean absolute error (MAE), mean absolute percentage error (MAPE) and Hit (%) in the calibration (Cal.) and validation (Val.) phases, in the state of São Paulo, Brazil.

Model	*r*		*d*		*c*		ME		MAE		Hit (%)	
	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.
NPBM18	0.93	0.80	0.96	0.88	0.89	0.70	0.06	-0.07	0.26	0.28	76	79
	r		***d***		***c***		**ME (days)**		**MAE (days)**		**MAPE (days)**	
#DTFB_T23	0.94	0.94	0.97	0.96	0.91	0.90	0	4.90	19.77	17.04	10.15	8.66

4.3.5. Monthly risks of eradiation of citrus trees with HLB symptoms

The maps of the monthly risks of eradication of citrus plants with HLB symptoms in the State of São Paulo are presented in Figure 11. The multiple linear regression models used to spatialize the variables that originated the risks are presented Appendix G, whereas the Appendix H contains both maps of NPBM18 (Appendix H1) and #DTFB_T23 (Appendix H2). Table 7 shows the statistical analysis of the models that generated the maps of NPBM18 and #DTFB_T23, which together resulted in the risk map. Both models had a performance ranging from good to very good. For NPBM18, the models presented *r* ranging from 0 to 0.94, *d* between 0 and 0.97, and *c* varying from 0 to 0.91. In both cases, zero represents when all estimated data were in the same class and observed risk was above of that. For #DTFB_T23, the statistical performance was similar (r = 0.82 to 0.97; d = 0.85 to 0.98; and c = 0.66 to 0.95). Throughout the months of the year, there is a variation in the risks of eradication of citrus trees with HLB symptoms (Figure 11). The months of January (Figure 11A), February (Figure 11B), March (Figure 11C), November (Figure 11K), and December (Figure 11L) were those with the lowest risks, with very low risk predominating in the state. In April (Figure 11B), and from August to October (Figures 11G, 11H, 11I, and 11J) the very low and low risk occurs in the north and increases to high and very high towards the south and the coast.. Finally, from April to July (Figures 11C, 11D, 11E, and 11F), the risks increase substantially, mainly in May and June when very high risk appears in the west.

(Continue)

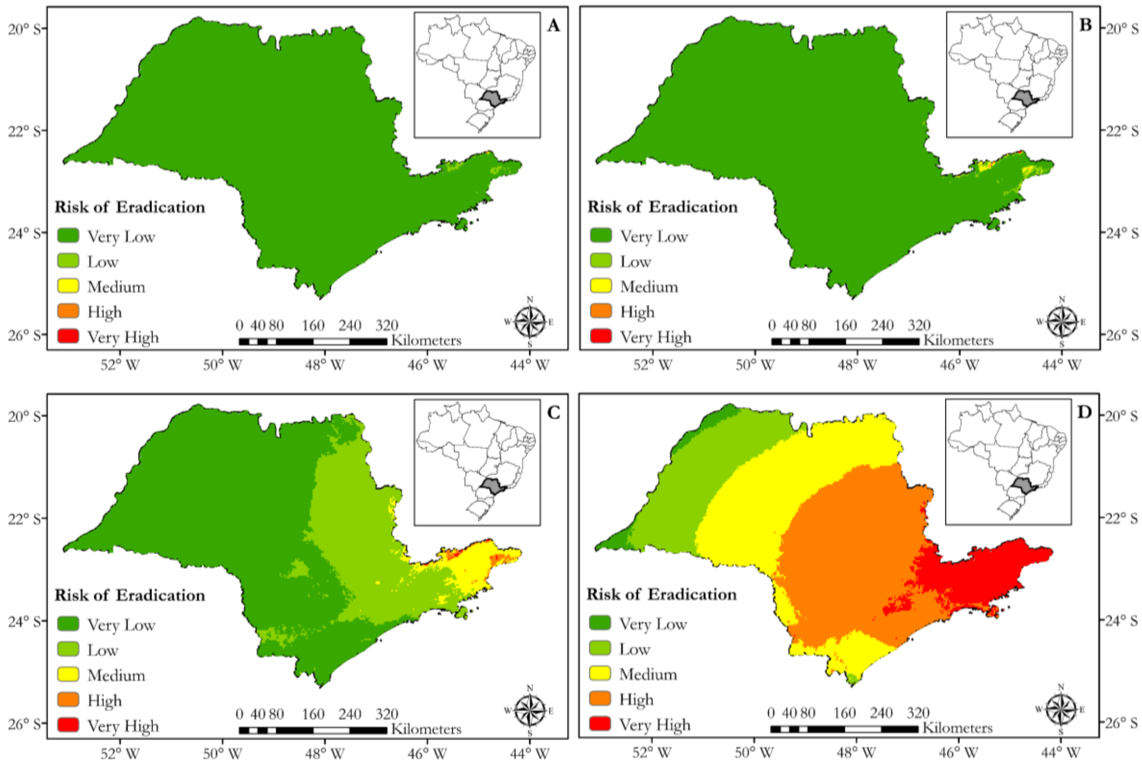

Figure 11. Monthly risks of eradiation of citrus trees with HLB symptoms in the state of São Paulo, Brazil, for: January (A); February (B); March (C); April (D); May (E); June (F); July (G); August (H); September (I); October (J); November (K); and December (L).

(Conclusion)

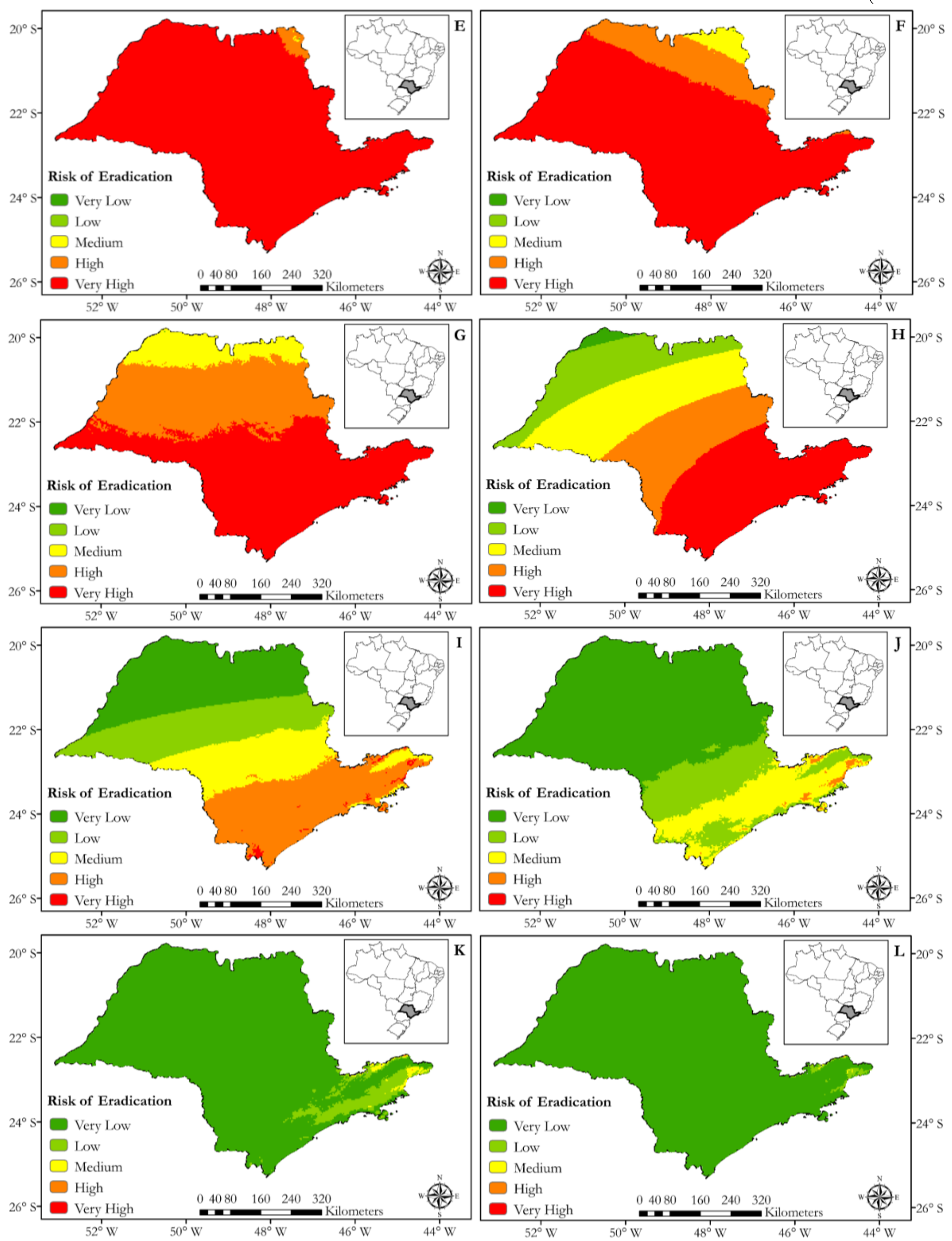

Figure 11. Monthly risks of eradiation of citrus trees with HLB symptoms in the state of São Paulo, Brazil, for: January (A); February (B); March (C); April (D); May (E); June (F); July (G); August (H); September (I); October (J); November (K); and December (L).

Table7. Performance of the models for estimating the number of psyllid per block per month 18 months before the eradication (NPBM18) and the number of days with average temperature below 23 °C in the month of eradication (#DTFB_T23), used to calculate the monthly risk of eradication of citrus trees with HLB symptoms, considering the correlation coefficient (*r*), Willmott agreement index (*d*), Camargo and Sentelhas confidence coefficient (*c*), mean error (ME), mean absolute error (MAE), mean absolute percentage error (MAPE) and Hit (%) in the calibration (Cal.) and validation (Val.) phases, in the state of São Paulo, Brazil.

Models	Months	*r*		*d*		*c*		ME		MAE		Hit (%)	
		Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.	Cal.	Val.
NPBM18	Jan	0	0	0.14	0.20	0	0	0.04	-0.07	0.04	0.07	96	93
	Feb	0.79	0.77	0.88	0.86	0.70	0.66	0.10	0.14	0.10	0.14	93	86
	Mar	0.90	0.84	0.94	0.91	0.85	0.76	0	-0.07	0.35	0.41	67	64
	Apr	0.89	0.86	0.94	0.92	0.83	0.79	0.03	-0.07	0.35	0.28	71	79
	May	0.94	0.77	0.97	0.86	0.91	0.66	-0,04	0.03	0.28	0.38	75	68
	Jun	0.88	0.83	0.93	0.91	0.82	0.76	-0.03	-0.07	0.29	0.41	73	64
	Jul	0.81	0.79	0.90	0.89	0.73	0.70	0.03	0.03	0.09	0.10	91	90
	Agu	0.70	0.73	0.84	0.86	0.59	0.63	0.09	-0.03	0.24	0.24	76	76
	Sep	0.75	0.72	0.86	0.84	0.64	0.61	0.09	0.14	0.18	0.28	82	72
	Oct	0.84	0.82	0.92	0.88	0.78	0.72	0	0.10	0.06	0.10	94	90
	Nov	0	0	0.02	0.12	0	0	-0.01	0.03	0.04	0.03	96	97
	Dec	0	0	0	0.12	0	0	0	0.03	0	0.03	100	97
		r		*d*		*c*		ME (dias)		MAE (dias)		MAPE (%)	
#DTFB_T23	Jan	0.88	0.87	0.93	0.90	0.82	0.78	0	0.66	2.41	1.88	0.57	0.53
	Feb	0.84	0.78	0.90	0.85	0.76	0.66	0	0.31	2.42	1.71	0.57	0.56
	Mar	0.89	0.87	0.94	0.91	0.84	0.80	0	0.44	2.69	2.31	0.42	0.44
	Apr	0.94	0.93	0.97	0.95	0.91	0.89	0	0.70	2.19	2.04	0.17	0.15
	May	0.88	0.89	0.93	0.93	0.82	0.82	0	0.62	1.81	1.71	0.07	0.07
	Jun	0.82	0.84	0.89	0.90	0.73	0.76	0	0.39	1.54	1.32	0.06	0.05
	Jul	0.84	0.86	0.91	0.91	0.77	0.78	0	0.57	1.82	1.57	0.07	0.06
	Agu	0.94	0.94	0.97	0.96	0.91	0.90	0	0.70	1.88	1.85	0.09	0.09
	Sep	0.97	0.96	0.98	0.98	0.95	0.94	0	0.16	1.50	1.26	0.09	0.08
	Oct	0.96	0.96	0.98	0.98	0.93	0.94	0	0.21	1.99	1.66	0.16	0.15
	Nov	0.93	0.93	0.96	0.96	0.89	0.89	0	0.40	2.31	1.93	0.24	0.22
	Dec	0.89	0.88	0.94	0.92	0.83	0.82	0	0.43	2.78	2.18	0.49	0.52

* Psyllid/Block x Number of Psyllid Generations

4.4. Discussion

Considering the complexity of the HLB pathosystem, its modeling is a great challenge for the citrus sector, as it involves aspects of the crop, related to the phase of development, to the psyllid, related to the temperature conditions for its development, and to the bacterium, associated to the temperature that favors its proliferation inside the plants. Although there are uncertainties in the model proposed in the present study, it had a satisfactory performance (Table 5), allowing to spatialize the risks for trees eradication, assisting the citrus growers in their crop planning and decision making regarding the HLB control. In addition, carrying out analysis in a more regionalized manner and not only by state, allows obtaining more detailed information about what occurs at the farm level, as well as obtaining information about what occurs each year, as well as in a given season of the year. The information contained in this study, with annual and monthly risks of eradication of citrus trees with HLB symptoms, based on climatic conditions, the citrus growers can analyze the conditions that favor the disease and, therefore, define the best actions to minimize the losses.

The eradication of citrus trees with symptoms of HLB is highly variable, since it depends on visual assessments and as the disease may show specific symptoms, sometimes it may not be diagnosticated in a precise manner, provoking underestimation of this variable at the field. In addition to that, symptoms can appear from 6 to 18 months (BOVÉ, 2006), and in some cases, these symptoms can appear just few months after infection (CANALE et al., 2016). Another aspect is that HLB infection of plants by a contaminated but asymptomatic one can occur from 2 to 4 months after infection, further contributing to the progress of the disease and increasing uncertainties about plants with symptoms in an orchard. Given these points, the modeling process represents a hard task, since there are several sources of uncertainties. Despite that, the proposed model performed satisfactorily, representing well what happened in the citrus farms in the state of São Paulo (Table 5, Figure 7).

Regarding the eradication estimation models, they were based on the psyllid population and conditions for the bacterium. Both models presented a very good performance and their weights for the final model were tested, resulting in 75% for the first and 25% for the last. According to Lopes et al. (2009) and Canale et al. (2016), transmission varies according to the psyllid's stage of development, and time since the acquisition of the bacterium and its transmission, and only the occurrence of the psyllid in greater numbers does not guarantee that the disease will occur in a high proportion.

Taking as example the study of Jesus Junior et al. (2008) with CVC, which is also caused by a bacterium transmitted by a vector, the present study considered the association of water deficit and trees eradication. This is mainly relevant since psyllid occurrence is based on water deficit followed by rainfall and favorable temperatures to start increasing of its population, which increases the infections and the number of trees eradication after some time. The greater water deficit makes the bacterium to be more concentrated in the phloem, what makes its acquisition by the psyllid easier, increasing the chances of infection. Due to this fact, the weight of psyllid occurrence in the final model was higher than the favorable temperature conditions to the bacterium. The weights used in the present model was different from those presented by Lopes et al. (2009) and Canale et al. (2016).

Regarding the temperature favorable for bacterium development and HLB detection, the species normally found in higher proportion in the state of São Paulo, is *Candidatus* Liberibacter asiaticus, which grows at higher temperatures when compared to *Candidatus* Liberibacter americanus and *Candidatus* Liberibacter africanus (LOPES et al., 2009). According to Gasparoto et al. (2012), the night temperature of 17 to 22 °C and daytime of 22 to 27 °C are those that most favor the HLB caused by *Candidatus* Liberibacter asiaticus. Considering that, the best adjustment for the risk of eradication model detection for the average temperature below 23 °C, which is within the limits presented by Gasparoto et al. (2012). These mild temperatures enable a good development of the bacterium and thus the disease will occur in high proportion in places with many days with temperatures below 23 °C. On the other hand, Lopes et al. (2009) found temperatures of 32 °C being favorable to the development of the bacterium, which was not related to the eradications in the sites studied by these authors. Taylor et al. (2019) found better transmission of the HLB causing bacterium by the psyllid when temperatures were up to 25 °C, a value closer to that found in the present study. This explains why the disease is less detected in the spring/summer months in São Paulo, since these seasons present high number of days with temperatures above 23 °C, the opposite being observed during the autumn/winter months (Figure 9 and 11). Allied to that, the intense water deficit conditions during the autumn/winter in the state of São Paulo promotes an increasing detection of infected tress, when mild temperatures favor the development of the bacteria.

Narouei-Khandan et al. (2016) found a high relationship between the occurrence of HLB and rainfall, considering 1200 mm annually as the total necessary for the establishment of the disease. According to Alvares et al. (2013), the average annual precipitation is within this range in the State of São Paulo being lower in the west. However, Taylor et al. (2019) found a higher relationship between the transmission of bacteria associated with temperature than precipitation, corroborating what was found in the present study.

According to Lopes et al. (2007), citrus HLB is found in a greater proportion in the south compared to the north and northeast of the state of São Paulo. This agrees with what was observed for the average of the years assessed (Figure 10). It happens because in these regions of São Paulo there is the combination of the occurrence of the psyllid and the temperature is more favorable to the development of the bacterium. When assessing monthly risks of trees eradication (Figure 11) the south and coast of the state becomes of higher risk, which can be explained by the lower temperature in these months of the year, in addition to the occurrence of the psyllid 18 months earlier. However, variations from year to year can occur, with years with more rainfall in the winter affecting the occurrence of sprouts estimated, anticipating the psyllids occurrence and, consequently, the transmission of the bacterium. Warmer autumns can also alter the occurrence of the bacterium, however, according to Bassanezi et al. (2010), the detection of trees with HLB symptoms is higher in the autumn and winter, as also showed in the present study.

Most of the models about HLB disease estimates the occurrence or risk of occurrence of the psyllid, and very few of them assess the psyllid occurrence together with the detection of plants with HLB symptoms. Narouei-Khandan et al. (2016) found a good fit for the models of occurrence of psyllid and HLB, with the first having a greater relationship with temperature and the second with temperature and rainfall. These authors found a high risk of detection of HLB in the entire state of São Paulo, different from what was found here. Such difference can be associated to the lack of details considered in the study of Narouei-Khandan et al. (2016), which reinforces the importance of interacting different aspects of HLB disease and not only psyllid population, even considering the limitations that these empirical models have. Even though, the risk of eradication model proposed here reflects well what happens in the state of São Paulo and can assist the citrus growers and consultants in choosing areas for citrus production expansion and for knowing when the disease should be monitored more frequently in the area, in order to facilitate the inspection of the area and detection of the plants with potential for eradication, aiming to reduce the dispersal of the disease in the orchard, reducing the impacts of this disease.

4.5. Conclusions

The eradication of citrus tree with symptoms of HLB is favored by the number of psyllids 18 months before the eradication, combined with an average temperature lower than 23 °C in the month of eradication. The final model of risk of eradication used these two variables in a proportion of 75% for the first and 25% for the second. For annual scale, the risk of eradication showed to be higher in the center and south of the state of São Paulo and lower in the north, in the same way, when monthly risks were assessed, with the higher risks occurring from March to June, mainly in the center and south of the state.

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SUPPLEMENTARY MATERIAL

Supplementary material 1. Performance of the models for estimating the relative eradication of citrus trees with HLB symptoms, during the calibration (Cal.) and validation (Val.) phases for five limits eradication in the state of São Paulo, Brazil: RErad_T22 – model considering number of days with temperature less than 22 °C; RErad_T23 – model considering number of days with temperature less than 23 °C; RErad_T24 – model considering number of days with temperature less than 24 °C; RErad_T25 – model considering number of days with temperature less than 25 °C.

	RErad_T22		**RErad_T23**		**RErad_T24**		**RErad_T25**	
	Cal.	**Cal.**	**Cal.**	**Cal.**	**Cal.**	**Val.**	**Cal.**	**Val.**
Limit 0.0025 of Relative Eradication								
CP	0.915	0.929	0.943	0.962	0.975	0.978	0.986	1.000
CN	0.222	0.130	0.160	0.072	0.099	0.058	0.062	0.014
Accuracy	0.569	0.530	0.552	0.517	0.537	0.518	0.524	0.507
Limit 0.0105 of Relative Eradication								
CP	0.896	0.911	0.928	0.952	0.959	0.976	0.973	0.984
CN	0.273	0.156	0.231	0.133	0.168	0.078	0.077	0.047
Accuracy	0.584	0.534	0.579	0.542	0.564	0.527	0.525	0.515
Limit 0.0255 of Relative Eradication								
CP	0.772	0.886	0.816	0.914	0.880	0.971	0.930	0.986
CN	0.364	0.242	0.311	0.220	0.238	0.148	0.146	0.071
Accuracy	0.568	0.564	0.564	0.567	0.559	0.560	0.538	0.529
Limit 0.0575 of Relative Eradication								
CP	0.648	0.630	0.648	0.630	0.725	0.741	0.780	0.815
CN	0.546	0.431	0.535	0.453	0.458	0.302	0.352	0.240
Accuracy	0.597	0.530	0.592	0.541	0.592	0.521	0.566	0.527
Limit 0.5 of Relative Eradication								
CP	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CN	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Accuracy	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500

* CP – Correct Positive – relation with the correct positive divided to false negative;

CN – Correct Negative – relation with the correct negative divided to false positive;

Accuracy - Average Correct positive and correct negative.

5. CLIMATIC RISK OF OCCURRENCE OF PSYLLID AND HUANGLONGBING IN CITRUS AS AFFECTED BY EL NIÑO SOUTHERN OSCILLATION IN SÃO PAULO, BRAZIL, AND FLORIDA, USA

ABSTRACT

Currently, huanglongbing (HLB) is the main disease in citrus orchards, being caused by a bacterium transmitted by a vector (psyllid). To know the factors that affect this disease is extremely important for defining the risks for its occurrence and how it can vary from year to year under different climatic conditions, mainly caused El Niño South Oscillation (ENSO) phenomenon. As the psyllid and the bacterium that causes HLB, as well as the citrus trees are directly influenced by weather conditions that affect their development, it is possible to use agrometeorological models for assessing the impacts of ENSO on HLB occurrence. Therefore, the objective of this study was to evaluate the effect of ENSO phases, considering their intensities, on the risks for psyllid occurrence and relative eradication of citrus trees with HLB symptoms, in a monthly and annual time scales. The study employed weather data from 1981 to 2015 from the following sources: Brazil – gridded weather data from Xavier's database for state of São Paulo; USA – gridded weather data from PRISM and NASA/POWER for state of Florida. The years, from July of year "n" to June of year "n+1" were classified according to the Equatorial Pacific Sea Surface Temperature Anomaly (SSTA), in the following ENSO phases: El Niño (EN); La Niña (LN); and Neutral (NE). To classify the intensities of each ENSO phase, the following interval of SSTA were used (at least with three months under these conditions): weak EN, SSTA between 0.5 °C and 0.9°C; moderate EN, SSTA between 0.9 °C and 1.4 °C; strong EN, SSTA > 1.4 °C; weak LN, SSTA between -0.5 °C and -0.9°C; moderate LN, SSTA between -0.9 °C and -1.4 °C; strong LN, SSTA < -1.4 °C. Firstly, the risk of occurrence of psyllid was calculated and the number of sprays for its control was determined and later associated with ENOS in their respective intensities for the state of São Paulo and Florida. After that, the relative eradication of citrus trees with HLB symptoms was calculated by the model that considers 75% of the number psyllid per block per month 18 months before the eradication and 25% of the number of days with favorable temperature for bacterium development. For the risk classification, five classes from 1 to 5 were considered (Very Low, Low, Medium, High, and Very High). Over the years the risk of psyllid occurrence was higher in the state of São Paulo under moderate La Niña, whereas in Florida it happened during strong La Niña events. When the monthly scale was considered, the highest risks of psyllid occurred during strong El Niño events in São Paulo, mainly in October, whereas the lowest risk was in in June. During El Niño of weak and moderate intensities, the highest risk of psyllid was again in October, whereas the lowest one was in February. In Florida, during the weak, moderate, and strong El Niño events, the lowest risk of psyllid occurred in February and the highest in June/July. At strong La Niña events in São Paulo, the risk of psyllid was higher in December and lower in March, while at moderate and weak events the risk was higher in October and lower in June/July. For Florida, the La Niña of any intensity, the lowest risk of psyllid was in February and the highest in May and July. Finally, the risk of psyllid occurrence during Neutral events in São Paulo was lower in July and higher in October and in Florida, it is lower in February and higher in July. For the risk of relative eradication, it was higher in São Paulo during Neutral in the year. Whereas during El Niño of all intensities such risk was higher from May to July. For La Niña of all intensities, the risk was higher from May to September. Finally, Neutral events presented the highest risks of eradication in the period from May to August.

Keywords: *Diaphorina citri*; *Candidatus* Liberibacter asiaticus; ENSO; Citrus; São Paulo; Florida.

5.1. Introduction

There are several challenges to produce citrus around the world, with the occurrence of diseases being the most important. Several diseases can affect citrus orchards, however, the most important one at the present is huanglongbing (HLB), also known as greening, which is bacterial (species *Candidatus* Liberibacter asiaticus and *Candidatus* Liberibacter americanus) disease transmitted by the psyllid (*Diaphorina citri*) (BOVÉ, 2006; LOPES et al. 2009; GASPAROTO et al. 2012). This disease was firstly reported in 1919 in China and then in Africa in 1937 (GRAÇA, 1991). In Brazil, the first report of HLB was in Araraquara, state of São Paulo, in 2004, (COLETTA-FILHO et al., 2004). One year later, HLB was also reported in Florida (HALBERT, 2005), and seven years later the disease was infecting orchards in California (KUMAGAI et al., 2013) and Texas (DA GRAÇA et al., 2015). Currently, HLB is the main citrus disease worldwide (GRAÇA, 1991; COLETTA-FILHO et al., 2004; BRUCE et al., 2005), being responsible for serious damages to citrus production and leading to eradication of millions of trees where the disease is not well managed.

Among the factor that affect HLB occurrence in citrus orchards, the weather conditions are the most important since they influence several aspects of the epidemics, as the availability of suitable citrus tissues (sprouts) to attract vector (CATLING, 1970; KRIEDEMANN, 1971; DAVIES AND ALBRIGO, 1994; LIU AND TSAI, 2000; NAVA et al., 2007 ; AURAMBOUT et al., 2009; MOSCHINI et al., 2010 ; PARRA et al., 2010; RAMOS et al., 2010 ; HALL et al., 2011; RIBEIRO et al., 2012 ; TORRES-PACHECO et al., 2013 ; LEE et al., 2015; SOARES-COLLETTI et al., 2016), the vector´s occurrence, development and abundance (DAVIS et al., 2005; NAVA et al., 2007; AURAMBOUT et al., 2009; MOSCHINI et al., 2010; TORRES-PACHECO et al., 2013; DIAZ-PADILHA et al. 2014; RAMIREZ et al., 2016), and bacterial proliferation (GASPAROTO et al., 2012; LOPES et al., 2009). Therefore, this disease and its control will have the influence of the weather conditions and their variability, which is mainly influenced by El Niño South Oscillation (ENSO) events.

ENSO is a large-scale phenomenon that occurs in the Equatorial Pacific Ocean, being composed of the oceanic and atmospheric components. The oceanic component manifests itself through changes in Sea Surface Temperature Anomaly (SSTA), while the atmosphere one is related to the variations in atmospheric pressure at the eastern and western ends of the Equatorial Pacific Ocean (BERLATO; FONTANA, 2003). ENSO has two phases, one with the cold SSTA, called La Niña, and the other with the warm SSTA, known as El Niño. In Brazil, ENSO impacts are variable depending on the region of the country. Normally, La Niña promotes an increase in rainfall in the north and northeast, a decrease in the south and in the southeast region there is no well-defined pattern in terms of rainfall variation. For air temperature, La Niña causes a decrease in temperatures during the winter in the southeast and northeast regions (MARENGO; DE OLIVEIRA, 2013). The main effects of the El Niño in Brazil are droughts of different intensities in the North and Northeast regions, an increase in average temperature in the Southeast region, a tendency for below-average rainfall in the Midwest region and high levels of precipitation in the South region (DE OLIVEIRA; SATYAMURTY, 1998; MARENGO, 2006; CIRINO et al. 2015; ROPELEWSKI; HALPERT, 1987). In the state of Florida, USA, El Niño events promote an increase in rainfall, whereas a decrease in this weather variable is normally observed in La Niña years (SCHMIDT et al., 2001). The increase in rainfall in Florida during El Niño years occurs from October to March, period when the temperatures tend to be lower (ROPELEWSKI; HALPERT, 1986).

Considering the aspects presented above, ENSO phases and their impacts on weather conditions promotes variations in citrus sprouting, psyllid occurrence, development, and bacteria proliferation, affecting HLB epidemiology. The weather conditions are the most responsible for the greatest detection of HLB during autumn and winter months (BASSANEZI et al., 2010). As ENSO impacts weather conditions and they affect HLB disease, it is expected that the different phases of this phenomenon have been affecting the HLB intensity, as also reported for Asian soybean rust in the state of Rio Grande do Sul, Brazil (DEL PONTE et al., 2011), coffee rust in Center-Southern Brazil (HINNAH et al. 2020), and *Eucalyptus* rust in all Brazilian regions (NÓIA JUNIOR et al., 2018). Once impacts of ENSO phases on disease intensity could be known, growers can adopt the best strategies to mitigate the damages caused by plant diseases. Regarding the effect of ENSO phases on HLB, there is still no study that investigated how different phases of this phenomenon can affect the risk of occurrence of psyllid and HLB. Therefore, the objective of this study was to evaluate the effect of the ENSO phenomenon on the risk of occurrence of psyllid and HLB and thus indicate years and months that demand greater attention for disease management.

5.2. Material and methods

5.2.1. Meteorological Data

The meteorological data used to calculate the risk of occurrence of psyllids and HLB were: maximum and minimum air temperature; solar radiation; relative humidity; rain; and wind speed. For São Paulo and Florida, data from the period 1981 to 2015 were used, considering gridded data (50 x 50 km) from the following databases: São Paulo - Xavier's database (Xavier et al., 2016), which has been largely used in Brazil, as reported by Duarte and Sentelhas (2020); USA - PRISM, which is the gridded weather database for USA, supported by the Oregon State University, and NASA/POWER, which was only used as the source of wind speed data for the Florida locations. In total, 85 sites were used for the state of São Paulo and 66 for the state of Florida.

5.2.2. Estimation of the number of psyllids per block

The estimation of the number of psyllids per block was done with the model that has as input the number of days in 14 days (X1) with the following conditions: water deficit ≥ 5 mm in 10 days, followed by rainfall ≥ 5 mm in 5 days and air temperature between 16 and 28 °C in at least 4 out 7 days, as presented in Equation 1:

$$\frac{Psyl.}{Bloc} = 0.3312 \times X1 + 1.7412 \tag{1}$$

The water deficit was estimated by daily water balance according to the method of Thornthwaite and Mather (1955) for a soil water holding capacity (SWHC) of 100 mm.

After calculating the number of psyllids per block, the required number of sprays was calculated for four thresholds, 1, 2, 3 and 4 psyllids per block, considering 7 days as the period of effective insecticide action. As the threshold of 1 and 2 psyllids per block presents an equal risk, and for the thresholds of 3 and 4 psyllids per block it was also the same.

With the number of sprays for psyllid control for the states of São Paulo and Florida, the risks were assigned to five different classes, according to the maximum and minimum values found, named as very low (1), low (2), medium (3), high (4), and very high (5).

5.2.3. Estimation of eradiation of citrus trees with HLB symptoms

For the estimation of HLB occurrence, the model for estimation of eradiation of citrus trees with HLB symptoms was used. The model for estimating the relative eradication (RErad) has as inputs the number of psyllids captured per block per month in the moment of bacterium transmission, considered as 18 months (NPBM18) and the number of days with average temperature below 23 °C in the month of eradication (#DTFB_T23). The weights of these two variables in the model were, respectively, 75% and 25%. More details about this model can be found in the Chapter 4 of this thesis.

$$RErad. = 0.0005\ x\ (NPBM18 \times 0.75) + 0.0095\ x\ (\#DTFB\_T23\ x\ 0.25) - 0.002 \tag{2}$$

5.2.4. ENSO phases and intensities

For the classification of different phases of El Niño South Oscillation (ENSO) in El Niño, La Niña and Neutral, the data available at the Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration (NOAA) was used. To classify a given year in one of the ENSO phases, the period between July of year "n" and June of year "n+1" was considered, according to the recommendation of Berlato and Fontana (2003). Thus, a year was considered as El Niño always that Pacific Ocean, at position 3.4, presented a SSTA equal or higher than 0.5 °C. When SSTA was equal or lower than -0.5 ºC, the year was classified as La Niña, whereas when the SSTA remained between -0.5 and 0.5, the year was named as Neutral. Table 1 presents the 34 years evaluated in this study and their respective phases associated to ENSO. For the classification of ENSO intensities, the classification of the Golden Gate Weather Services (2020) was used: weak EN, SSTA between 0.5 °C and 0.9°C; moderate EN, SSTA between 0.9 °C and 1.4 °C; strong EN, SSTA > 1.4 °C; weak LN, SSTA between -0.5 °C and -0.9°C; moderate LN, SSTA between -0.9 °C and -1.4 °C; strong LN, SSTA < -1.4 °C.

Table 1. Classification of the years of the period from 1981 to 2015 according to their ENSO phase (Neutral, El Niño and La Niña) and their intensity, as recommend by CPC/NOAA and Golden Gate Weather Service.

Year	ENSO phase	Intensity	Year	ENSO phase	Intensity
1981-1982	Neutral	Weak	**1998-1999**	La Niña	Strong
1982-1983	El Niño	Strong	**1999-2000**	La Niña	Strong
1983-1984	La Niña	Weak	**2000-2001**	La Niña	Weak
1984-1985	La Niña	Weak	**2001-2002**	Neutral	Weak
1985-1986	Neutral	Weak	**2002-2003**	El Niño	Moderate
1986-1987	El Niño	Moderate	**2003-2004**	Neutral	Weak
1987-1988	El Niño	Strong	**2004-2005**	El Niño	Weak
1988-1989	La Niña	Strong	**2005-2006**	La Niña	Weak
1989-1990	Neutral	Weak	**2006-2007**	El Niño	Weak
1990-1991	Neutral	Weak	**2007-2008**	La Niña	Strong
1991-1992	El Niño	Strong	**2008-2009**	La Niña	Weak
1992-1993	Neutral	Weak	**2009-2010**	El Niño	Moderate
1993-1994	Neutral	Weak	**2010-2011**	La Niña	Strong
1994-1995	El Niño	Moderate	**2011-2012**	La Niña	Moderate
1995-1996	La Niña	Moderate	**2012-2013**	Neutral	Weak
1996-1997	Neutral	Weak	**2013-2014**	Neutral	Weak
1997-1998	El Niño	Strong	**2014-2015**	El Niño	Weak

5.2.5. Data analysis

The effect of the ENSO phases, every year, on the risk of occurrence of psyllid or HLB were assessed considering their intensities as described above. For such purpose, the risks were plotted for all locations of São Paulo, Brazil, and Florida, USA, for each years of the historical series. The results were presented in box-plot graphs for each state and considering the two levels of threshold (1 and 2 psyllids per block; 3 and 4 psyllids per block).

5.3. Results

5.3.1. Effect of ENSO phases and intensities on the risk of psyllid occurrence

Figure 1 presents the risk of psyllid occurrence associated to the different phases of ENSO and their intensities for the state of São Paulo, along the period from 1981 to 2015, for the two levels of threshold considered. On average, for both levels of threshold, the highest average risk is associated with Neutral years, followed by La Niña and El Niño. When considering the intensities of the ENSO phases, years with weak El Niño and moderate La Niña presented higher risks, with the latter being slightly higher. In the sequence, medium risks were observed for weak La Niña, followed by Neutral years, and moderate El Niño. The lowest risks happened during strong events of La Niña and El Niño, with the last one presenting the smallest risks.

When the risks of occurrence of the psyllid in São Paulo, Brazil (Figure 1), was compared to the risks in the state of Florida, USA (Figure 2), it is possible to observe that independently of the ENSO phase, the risks in Florida were higher than in São Paulo. Whereas in São Paulo the average risk for psyllid occurrence was high, for Florida it was very high. On average, for Florida, during the years with the La Niña the risks were higher than Neutral and El Niño years, with El Niño events showing the lowest risks. When the intensity of the ENSO phases was considered, the highest average risk occurred under strong La Niña events, followed by weak El Niño, weak La Niña, Neutral, moderate La Niña, and strong and moderate El Niño events for both threshold levels considered.

Figure 3 shows the monthly variation of psyllid occurrence risks in years of El Niño, in its three intensities for both thresholds for control decision, in the state of São Paulo. It is possible to observe that the risks of psyllid occurrence, on average, is higher in the second half of the year, mainly in October and November. In most of the months, the highest risks are associated to weak El Niño, followed by strong and moderate events of this ENSO phase. The highest risk is in October and the lowest in February, for weak and moderate El Niño events, whereas for the strong ones the highest risk also occurs in October, but the lowest in June. In all the intensities of this ENSO phase, the risk starts to rise in August and reaches its peak between October and November, declining after that, independently of the control threshold considered (Figure 3).

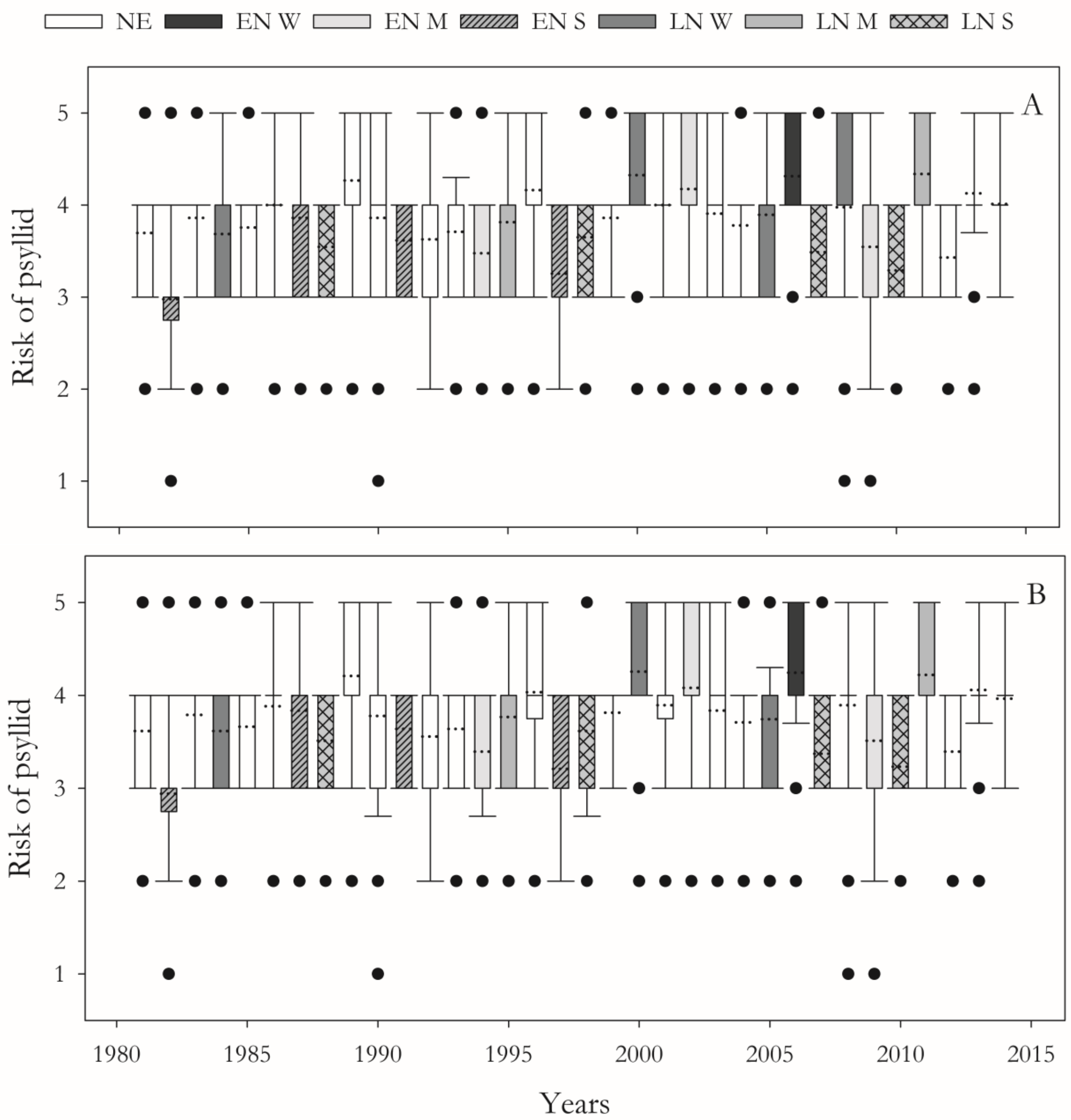

Figure 1. Annual risk of psyllid occurrence in 86 sites of the state of São Paulo, Brazil, for the two levels of threshold for recommending the control: 1-2 psyllids per block (A) and 3-4 psyllids per block (B), for the period of 34 years (1981-2015), considering the different phases of ENSO (Neutral – NE; El Niño – EN; and La Niña – LN) and their intensities (weak – W; moderate – M; and strong – S). The dotted lines indicate the average.

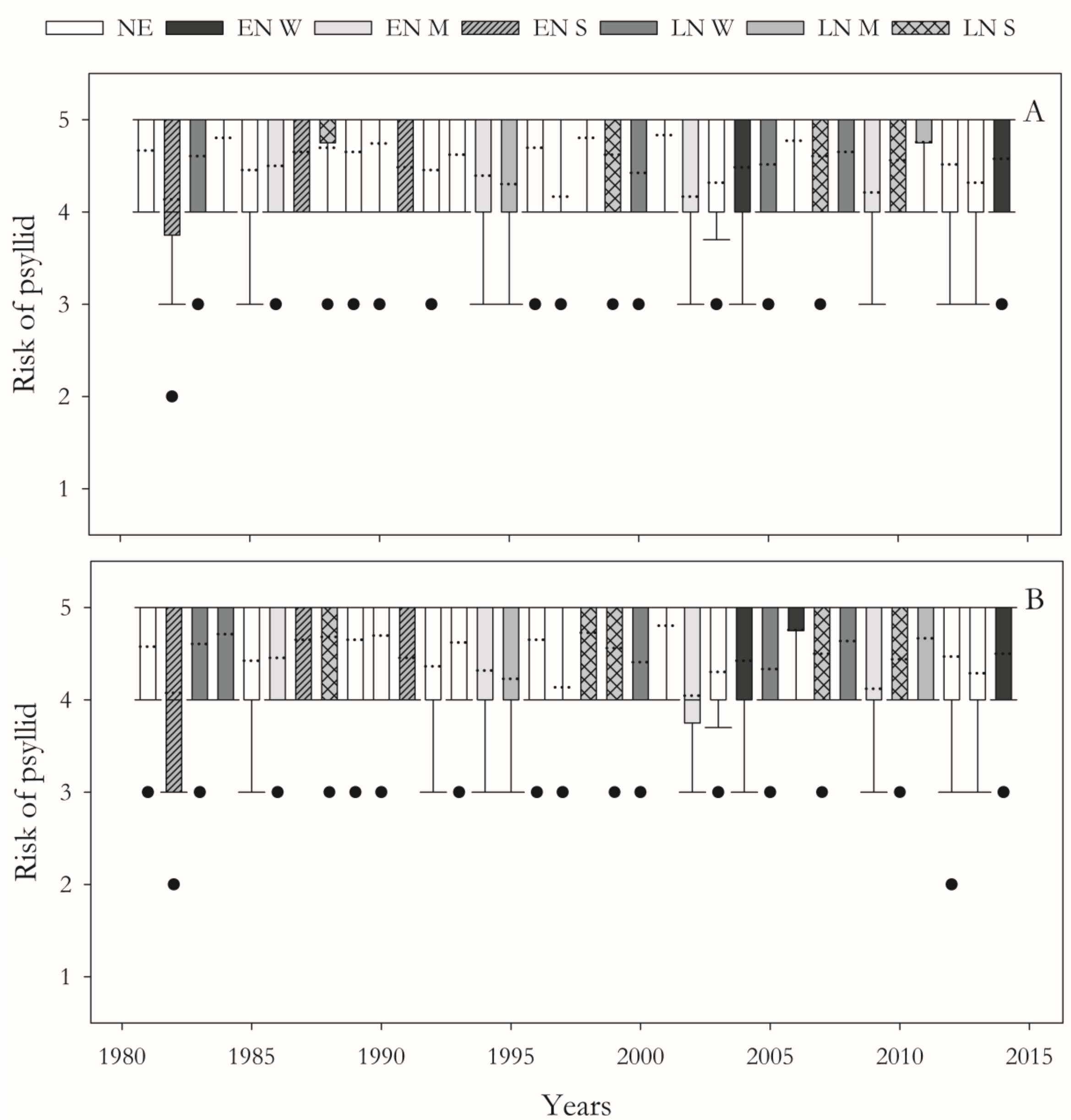

Figure 2. Annual risk of psyllid occurrence in 66 sites of the state of Florida, USA, for the two levels of threshold for recommending the control: 1-2 psyllids per block (A) and 3-4 psyllids per block (B), for the period of 34 years (1981-2015), considering the different phases of ENSO (Neutral – NE; El Niño – EN; and La Niña – LN) and their intensities (weak – W; moderate – M; and strong – S). The dotted lines indicate the average.

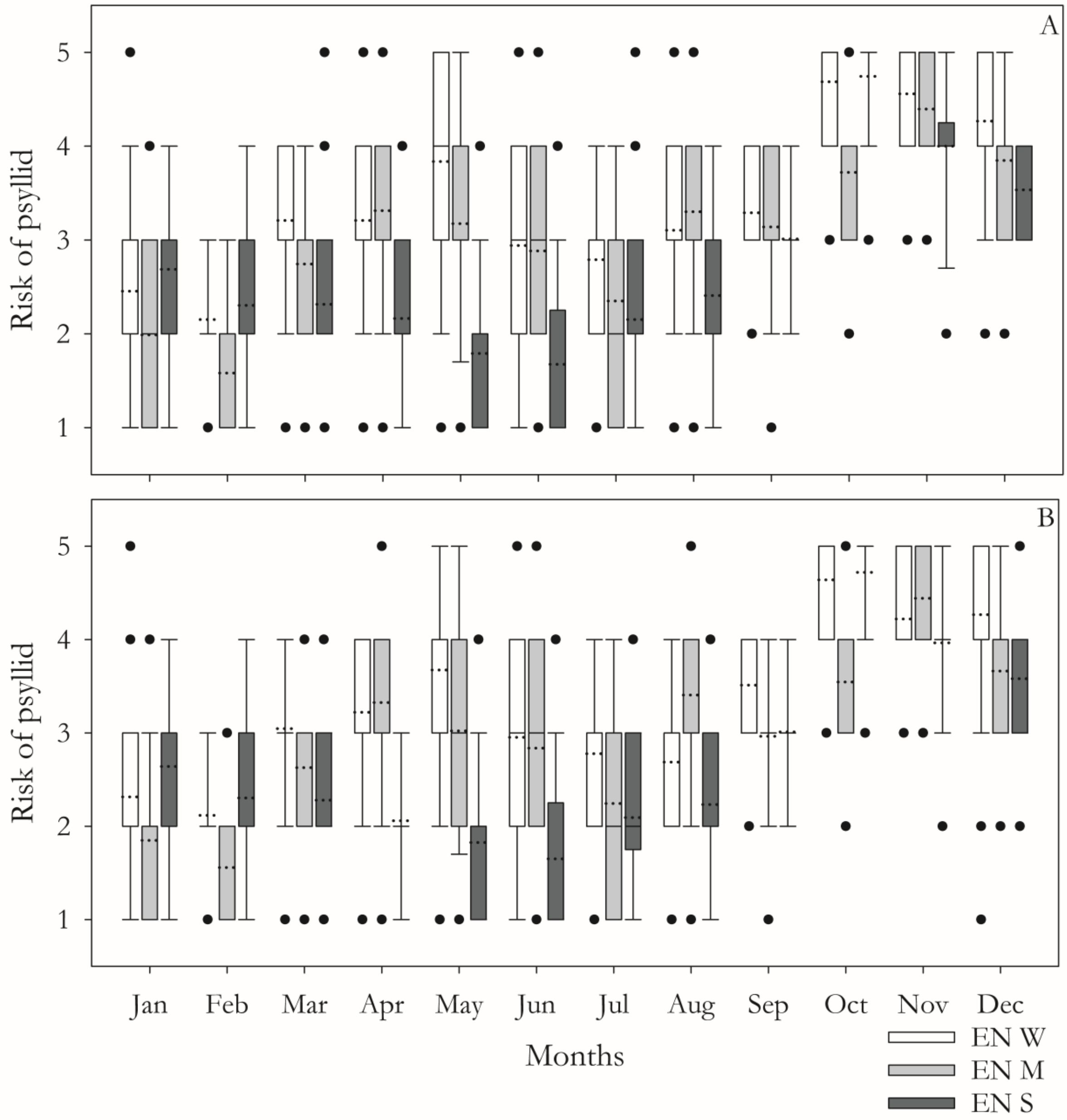

Figure 3. Monthly risk of psyllid occurrence in 86 sites of the state of São Paulo, Brazil, for the two levels of threshold for recommending the control: 1-2 psyllids per block (A) and 3-4 psyllids per block (B), for the period of 34 years (1981-2015), considering only El Niño (EN) events, with different intensities (weak – W; moderate – M; and strong – S). The dotted lines indicate the average.

For the state of Florida, the risk of psyllid occurrence during El Niño events is between May and July, independently of the intensity of the event and the threshold considered (Figure 4). Different from Brazil (Figure 3), where the highest risks occur in the second semester, but mainly in October and November, in Florida (Figure 4) the highest risks occur from May to July, with low spatial variability among the 66 sites assessed, and, also, from October to December, but with a high spatial variability among the citrus producing regions of the state. In most of the months, the greatest risk is associated with weak El Niño, except for February and March. From December to

April, there is a huge spatial variability among the sites assessed for Florida for all ENSO phases, mainly for the events with medium intensity.

Figure 5 shows the monthly variation in the risk of psyllid occurrence in the years with La Niña, under the three assessed intensities. Different from what was observed during El Niño years (Figure 3), the events of La Niña with a moderate intensity presented a higher risk in most months, which was followed by the events with weak and strong intensities. However, the highest risks remain occurring in the second semester, mainly between October and December. And under strong La Niña, for both thresholds. On the other hand, the lowest risks occurred in the first half of the year, especially between February and April for strong La Niña, and in July for strong and weak events. In the other months, the risks oscillated between medium and high, as presented in Figure 5.

Like what was observed for El Niño years (Figure 4), during La Niña events in Florida (Figure 6), the highest risks for psyllid occurrence were observed from May to July, with no clear tendency among the intensities of the phenomenon. January and February were the months with the lowest risks, whereas for March, April and from August to December, the risks oscillated a lot, with no many differences among the La Niña intensities, except for August and September when weak events shoed a higher risk for psyllid occurrence.

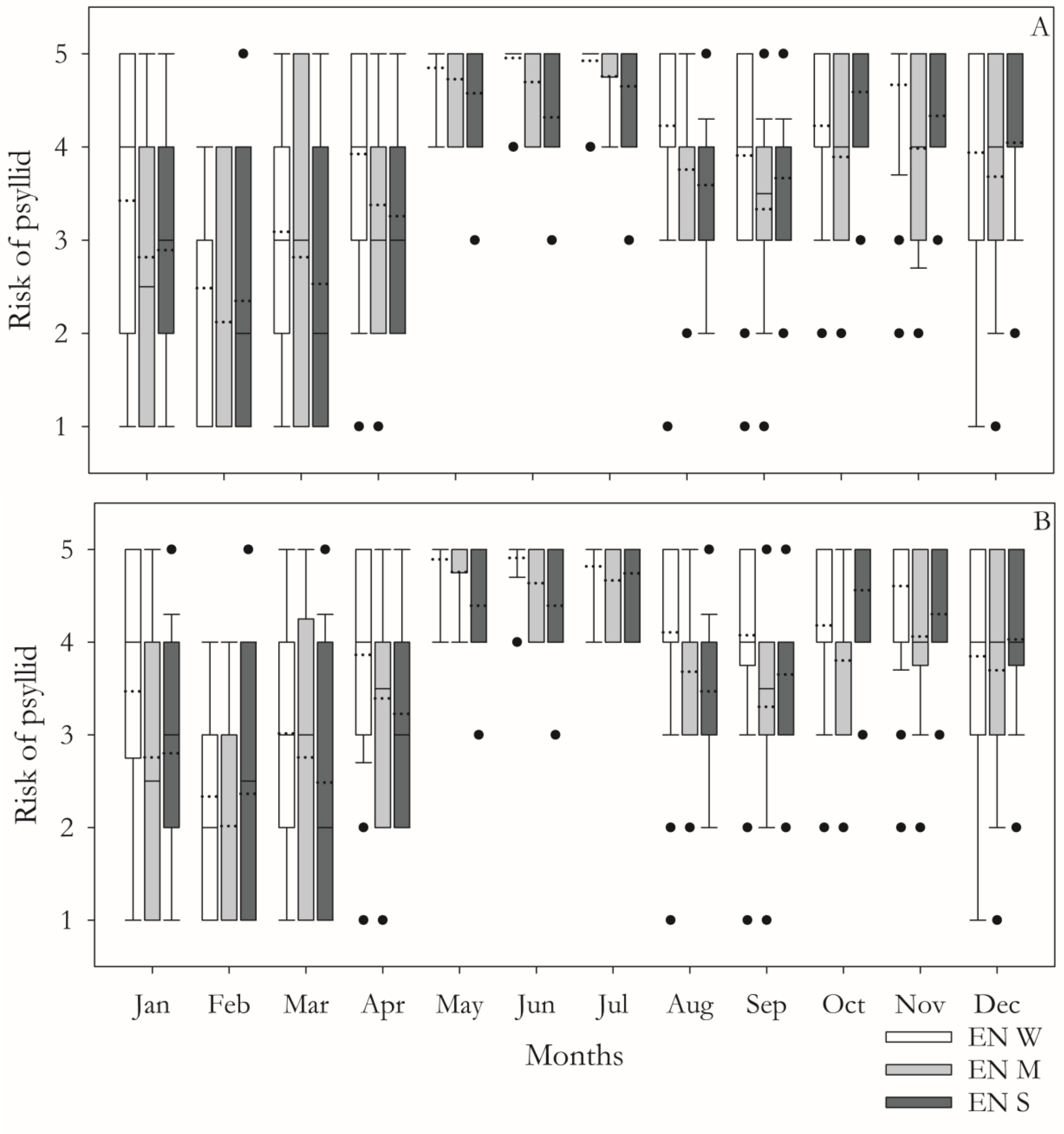

Figure 4. Monthly risk of psyllid occurrence in 66 sites of the state of Florida, USA, for the two levels of threshold for recommending the control: 1-2 psyllids per block (A) and 3-4 psyllids per block (B), for the period of 34 years (1981-2015), considering only El Niño (EN) events, with different intensities (weak – W; moderate – M; and strong – S). The dotted lines indicate the average.

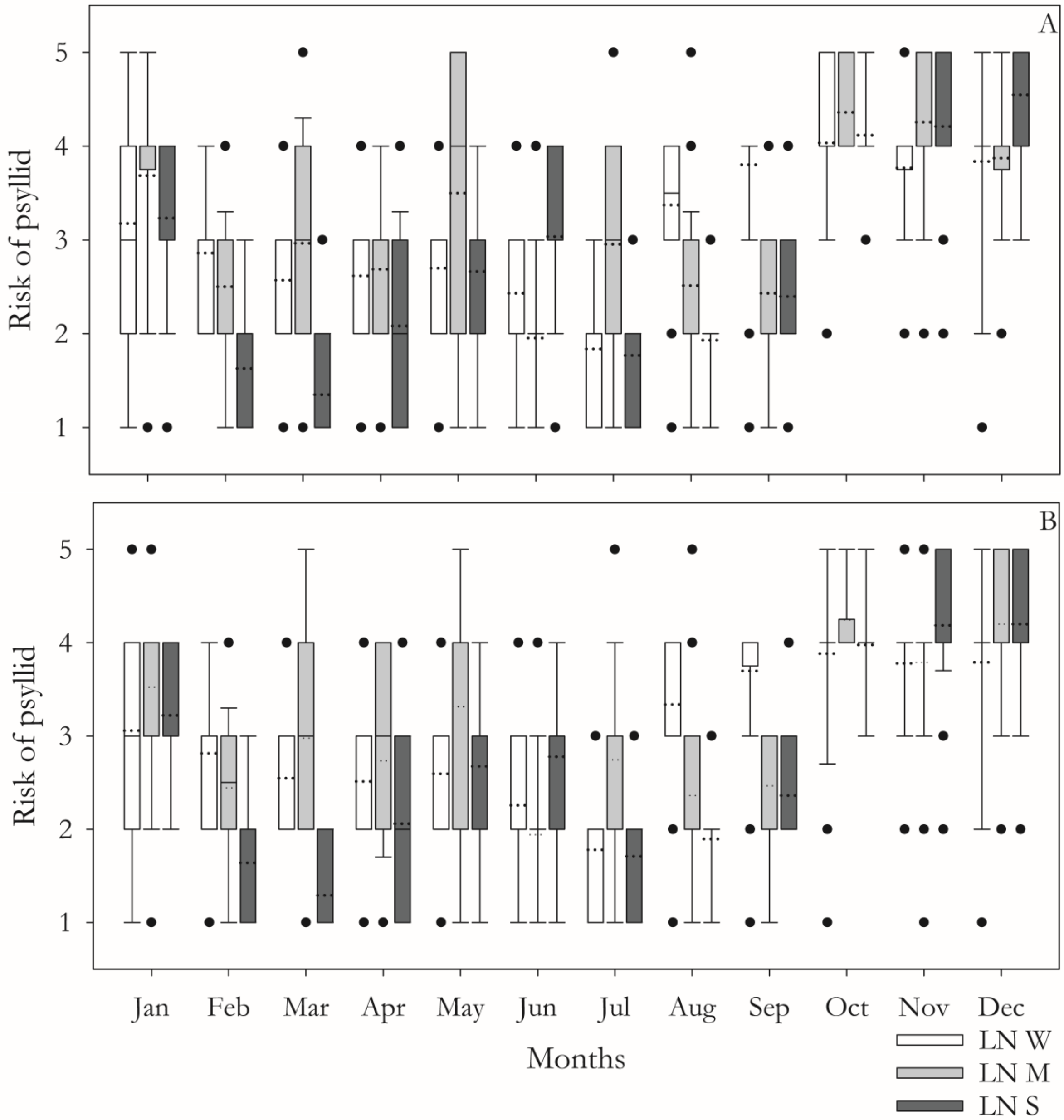

Figure 5. Monthly risk of psyllid occurrence in 86 sites of the state of São Paulo, Brazil, for the two levels of threshold for recommending the control: 1-2 psyllids per block (A) and 3-4 psyllids per block (B), for the period of 34 years (1981-2015), considering only La Niña (LN) events, with different intensities (weak – W; moderate – M; and strong – S). The dotted lines indicate the average.

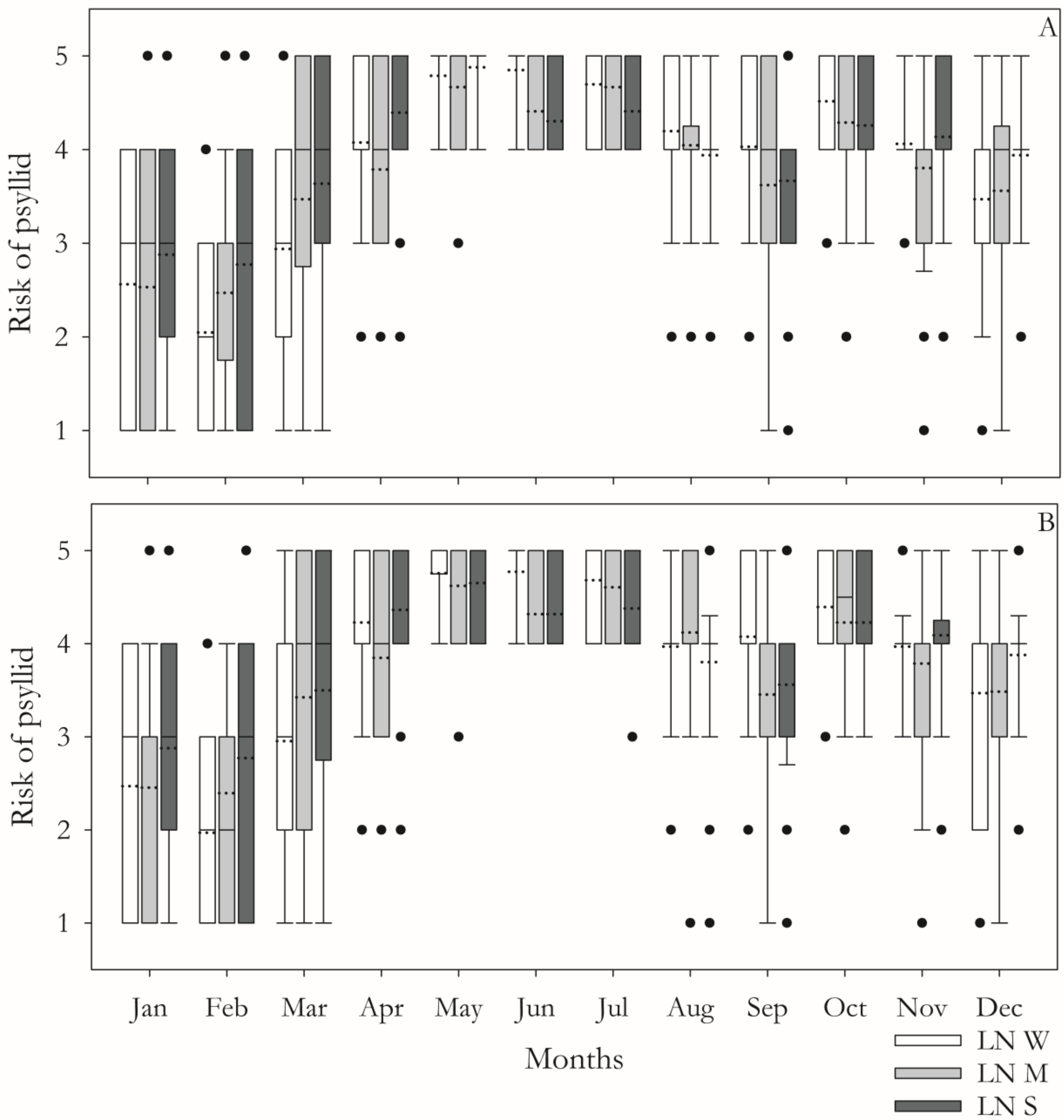

Figure 6. Monthly risk of psyllid occurrence in 66 sites of the state of Florida, USA, for the two levels of threshold for recommending the control: 1-2 psyllids per block (A) and 3-4 psyllids per block (B), for the period of 34 years (1981-2015), considering only La Niña (LN) events, with different intensities (weak – W; moderate – M; and strong – S). The dotted lines indicate the average.

Figures 7 and 8 show the monthly risk of psyllid occurrence during Neutral ENSO events for the states of São Paulo and Florida, respectively. For São Paulo (Figure 7), during Neutral events and for both thresholds used, the risks are moderate from February to August, after when they remain high and very high from September to January, with the peak of risk October and December. For the state of Florida (Figure 8), the risks for psyllid occurrence follows the same pattern presented during El Niño (Figure 4) and La Niña (Figure 6) events. For these Neutral events, monthly risks of psyllid occurrence were predominantly high and very high, with May and June presenting the peak of the risk.

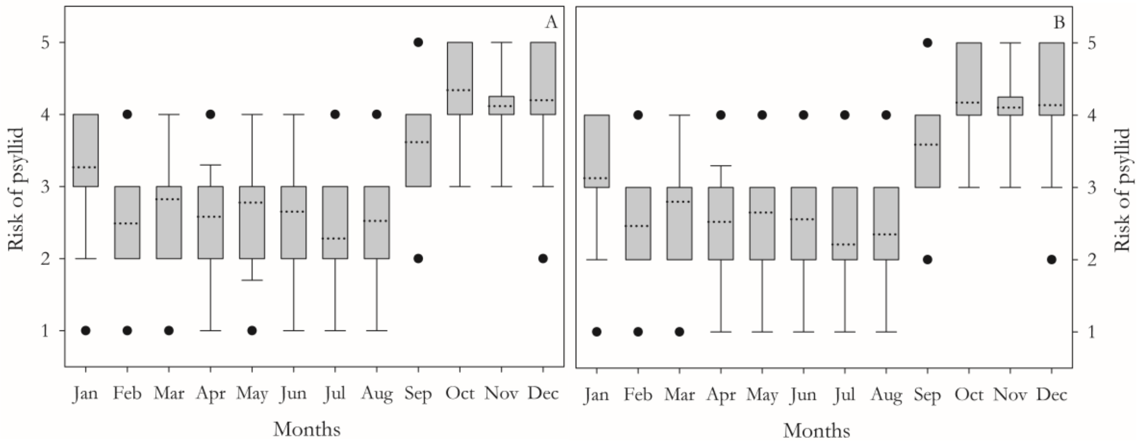

Figure 7. Monthly risk of psyllid occurrence in 86 sites of the state of São Paulo, Brazil, for the two levels of threshold for recommending the control: 1-2 psyllids per block (A) and 3-4 psyllids per block (B), for the period of 34 years (1981-2015), considering only Neutral events. The dotted lines indicate the average.

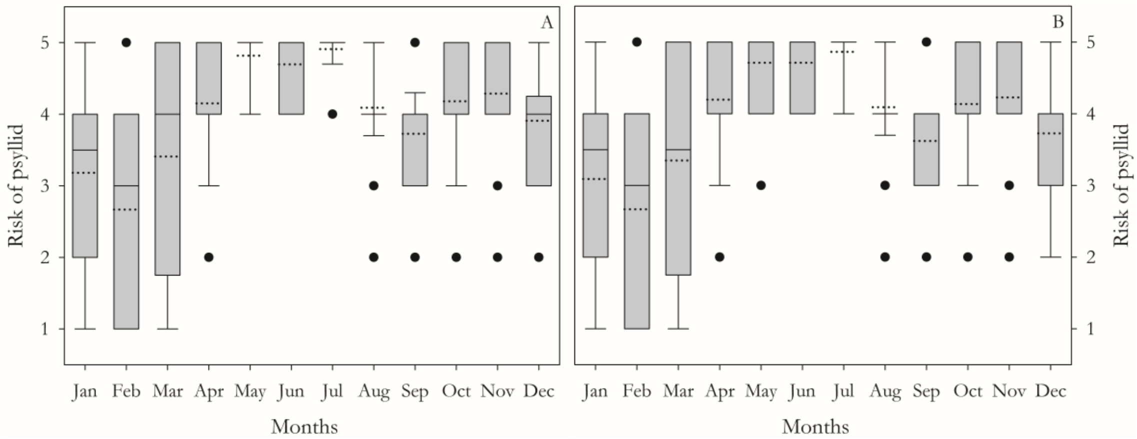

Figure 8. Monthly risk of psyllid occurrence in 66 sites of the state of Florida, USA, for the two levels of threshold for recommending the control: 1-2 psyllids per block (A) and 3-4 psyllids per block (B), for the period of 34 years (1981-2015), considering only Neutral events. The dotted lines indicate the average.

5.3.2. Effect of ENSO phases and intensities on the risk of citrus tree eradication as consequence of HLB disease in the state of São Paulo

When the analysis of the risks for eradication of citrus trees with HLB symptoms was considered, the results showed that Neutral years were those with the highest values along the historical series assessed (Figure 9), with most of the years with this event presenting very high risk. When assessing the intensity of the phenomenon, excluding Neutral years, strong La Niña events had higher risk than weak El Niño, weak La Niña, strong and moderate El Niño and finally moderate La Niña.

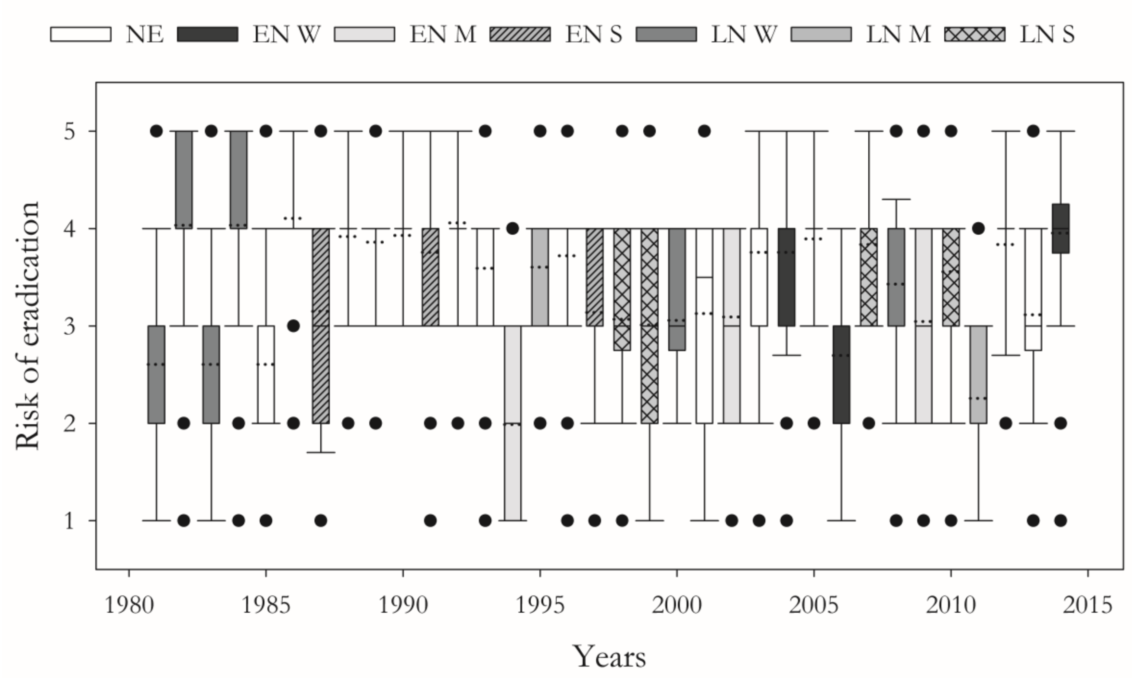

Figure 9. Annual risk of citrus trees eradication in 86 sites of the state of São Paulo, Brazil, for the period of 34 years (1981-2015), considering the different phases of ENSO (Neutral – NE; El Niño – EN; and La Niña – LN) and their intensities (weak – W; moderate – M; and strong – S). The dotted lines indicate the average.

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Considering now monthly risk only for El Niño events, the results showed different tendencies when its consequences to the risk of eradication was associated with each intensity of the phenomenon (Figure 10). The risks were lower in years of strong and weak El Niño followed by moderate one. In years of weak El Niño, the risk was low from January to March, increasing after that until its peak in May to July and decreasing after that. In moderate El Niño, the risks were higher from May to August. Finally, for the strong events, the highest risk of eradication was in May, followed by June and July. For the remaining months, the risks were lower, mainly from October to December and January to March.

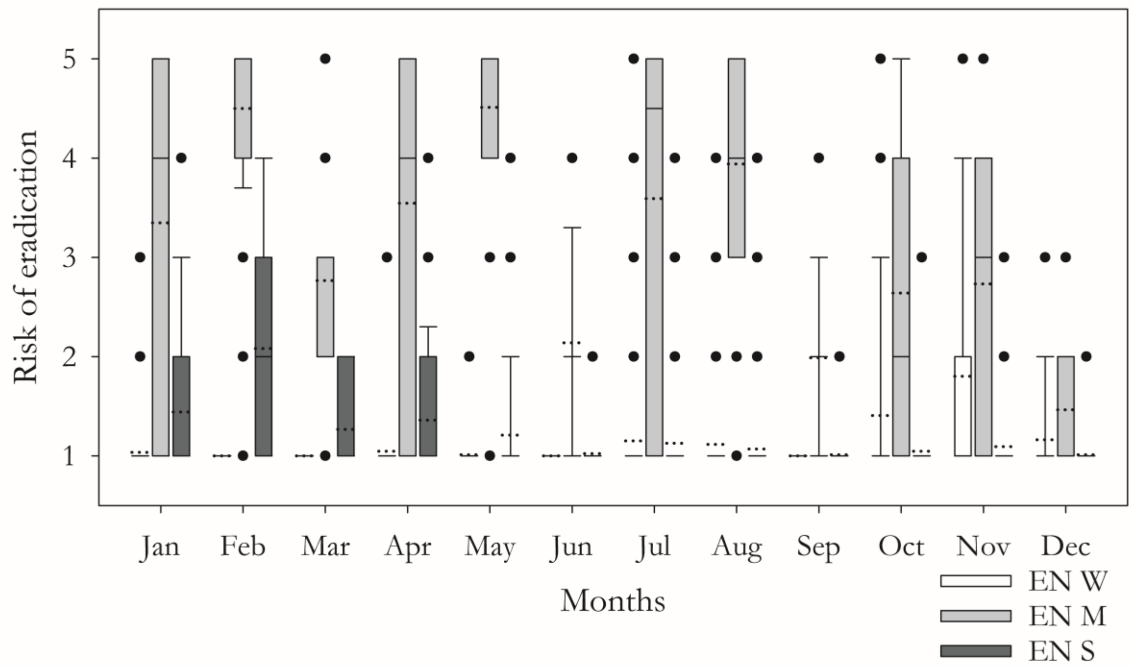

Figure 10. Monthly risk of citrus trees eradication in 86 sites of the state of São Paulo, Brazil, for the period of 34 years (1981-2015), considering El Niño events of ENSO with their different intensities (weak – W; moderate – M; and strong – S). The dotted lines indicate the average.

For the La Niña events in the state of São Paulo, the risk for citrus tress eradication showed distinct variations according to the intensity of the phenomenon (Figure 11). In the years of weak intensity, the risks were lower in the beginning and ending of the year, increasing from May to September. For the strong events the risk is higher from April to October. In moderate La Niña the risks remained high from April to October, but mainly from May from July.

Finally, for the Neutral ENSO phase, the risk of eradication, presented in Figure 12, showed a seasonal variation, with low risk from November to March, intermediated ones in April and from September to October, whereas from May to August the risks were high to very high.

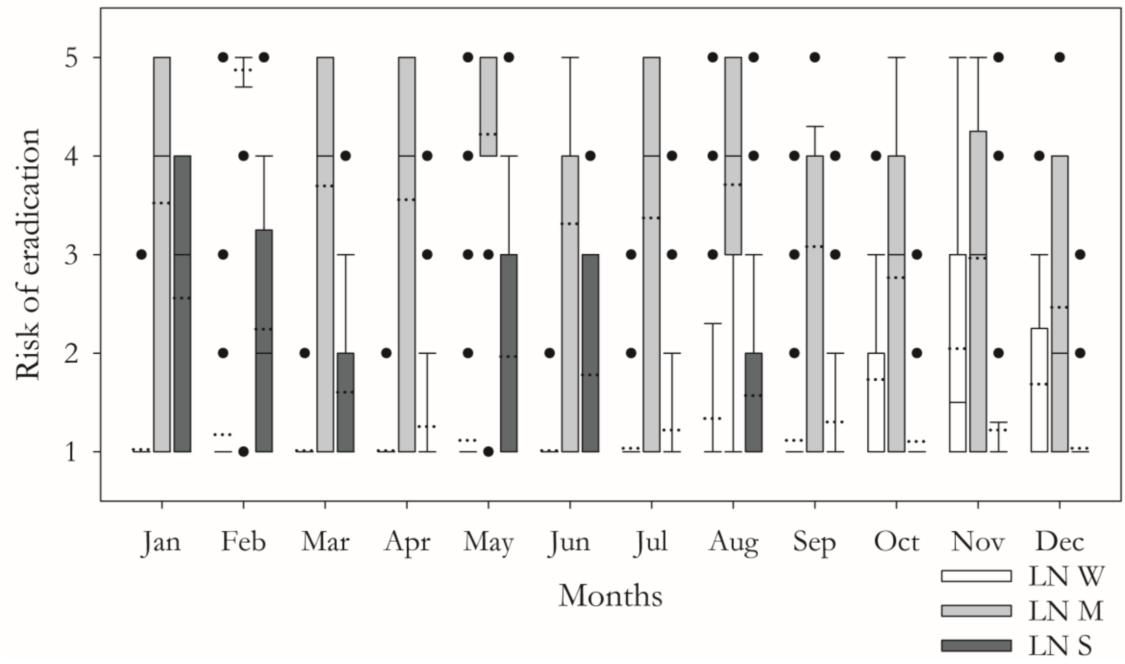

Figure 11. Monthly risk of citrus trees eradication in 86 sites of the state of São Paulo, Brazil, for the period of 34 years (1981-2015), considering La Niña events of ENSO with their different intensities (weak – W; moderate – M; and strong – S). The dotted lines indicate the average.

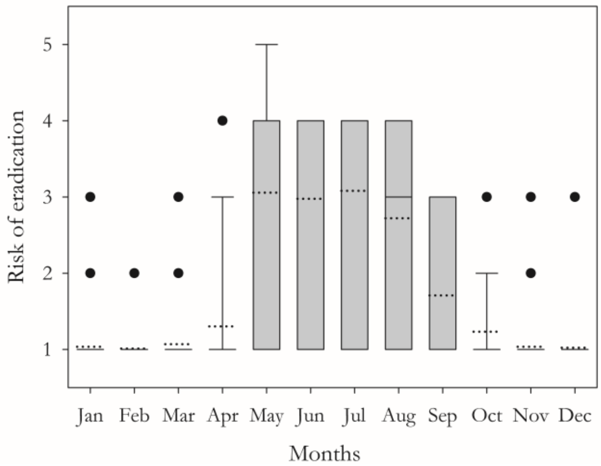

Figure 12. Monthly risk of citrus trees eradication in 86 sites of the state of São Paulo, Brazil, for the period of 34 years (1981-2015), considering Neutral events of ENSO. The dotted lines indicate the average.

5.4. Discussion

ENSO does not have clear patterns of rainfall anomaly in southeastern Brazil (DE OLIVEIRA; SATYAMURTY, 1998; MARENGO; DE OLIVEIRA, 2013), but even so, it has an effect that varies depending on its phase and intensity on the risk of occurrence of psyllid and HLB. In the United States, mainly in Florida, the ENSO effects on rainfall anomaly is clearer (SCHMIDT et al., 2001), which makes the risk associated to the HLB on citrus orchards variable, depending on the phases of the phenomenon and their intensities, as proved in the present study.

Considering the intensity of the phenomenon in the state of São Paulo, the annual risk is higher in moderate La Niña (Figure 1), which can be associated to the lower temperatures associated with this phenomenon (MARENGO; DE OLIVEIRA, 2013), since there are no patterns of anomalies for rainfall. Under these conditions, the estimated occurrence of citrus sprouting becomes longer, with more time with tender tissues that attract psyllids. Considering the annual risk of occurrence of HLB, that involves the occurrence of the vector and the development of the bacterium, there is a difference depending on the ENOS event (Figure 9). In neutral years, the risk is higher, followed by strong La Niña and weak El Niño.

In the state of Florida, the risk of occurrence of the psyllid is greater in the events of strong La Niña (Figure 2), when rainfall is lower (SCHMIDT et al., 2001), which increases the events of water deficit, promoting more sprouts availability when the rainfall returns. Such condition makes the sprouts more attractive to the psyllids, promoting a rapid increase in the vector´s population and chances of bacterium transmission. On the other hand, the lower risks were during El Niño years, which is associated with more rainfall and lower temperatures from September to March (ROPELEWSKI; HALPERT, 1986), conditions less favorable for psyllid.

Considering the monthly climatic risk of occurrence of the psyllid in Florida associated with the ENOS phenomenon, it varies depending on the phases and less on their intensities (Figures 4, 6 and 8). In Neutral years, the lower risk of occurrence of the psyllid is in February and higher in June, this is due to the climatic conditions, which normally present lower rainfall and temperatures during the winter, and during the summer both variables increase (ACKERMAN, 1941; PEEL et al., 2007). In the El Niño events of all intensities, the peak occurs in June/July and the lowest risk values is in February, what is caused by an increase in rainfall in the summer (SCHMIDT et al., 2001; ROPELEWSKI; HALPERT, 1986) and decrease in temperature during autumn and winter (ROPELEWSKI; HALPERT, 1986). In La Niña years, the risk of psyllid occurrence is lower in February and higher in May, under all intensities. The greatest risk in spring in La Niña years is caused by the intense water deficit in this period followed by rainfall, which favor sprouting and then induce increasing risk (SCHMIDT et al., 2001), once normally this period of the year is rainier (ACKERMAN, 1941; PEEL et al., 2007).

When the risk of occurrence of the psyllid and the associated ENOS events for the state of São Paulo over the months were evaluated, it was noticed a variation of the associated peak in the different intensities of the phases of the phenomenon (Figures 3, 5 and 7). In Neutral years, peaks occurred equally in October and lower risk values in July, reflecting the climatic conditions of the state, which limits the psyllid during autumn/winter due to water deficit and thermically in the summer (ALVARES et al., 2014). When we analyze the El Niño at different intensities, the weak and moderate events showed the lowest risk in February and the highest in October/November, whereas in the strong events only the lowest values differed in June. According to De Oliveira and Satyamurty (1998) and Guimarães and Dos Reis (2017), in El Niño years, the maximum and minimum temperatures are higher throughout Brazil, which may cause limitation for the psyllid during the summer, reducing the risk of its occurrence. However, when comparing the Neutral years with El Niño, it is noticed that in the summer the risk is lower in the latter, which reflect the influence of higher temperatures on that. Finally, in the case of weak and moderate La Niña, the risk peaks of the vector occurrence is in October and lower in June/July, whereas in the high intensity event the lowest risk value occurs in March and the highest in December. This can be explained by the lower temperatures recorded in this event (GUIMARÃES; DOS REIS, 2017; MARENGO; DE OLIVEIRA, 2013), intensifying what occurs in the normal climatic conditions of neutral years, that is, the risks are lower during autumn/winter and higher in spring/summer, due to lower temperatures.

Finally, the monthly risk of occurrence of HLB (tree eradication) has no difference at the peak, but only for the different intensities (Figures 9, 10, 11 and 12). Thus, in all ENOS intensities and events, the risk is greater in autumn and winter, what is due to the more favorable temperature during this period of the year in the state of São Paulo (Alvares et al., 2014). As the psyllid, population considered in the model refers to 18 months before the eradication, the eradication risk observed for autumn and winter refers to the psyllid number in spring and summer, when in general the risk of psyllid occurrence is higher. As the HLB model only considers air temperature as input, during the periods of the year when lower temperatures predominate are when the greatest number of plants with positive detection of the bacterium that causes HLB is observed. In addition, according to Maia et al. (2016), when heavy rainfall occurs the residual effect of insecticides for psyllid control is less effective. Thus, as in La Niña years in the state of São Paulo, Brazil, there is no pattern of rainfall change, there is no effect on such residual period, which keeps the control effective under this ENSO phase. In view of what was presented, ENSO has a variable effect on the risk of occurrence of the psyllid for the state of São Paulo, and there is a variation in its peak due to the phenomenon, being slightly different in years of strong and moderate La Niña in May, and in weak intensities of ENSO in June. Therefore, the risk of occurrence of HLB, represented by the number of eradications of citrus trees with disease symptoms, has a variable effect in the different ENSO events in this Brazilian state.

5.5. Conclusions

The risk of occurrence of the psyllid in the state of São Paulo, Brazil, and Florida, USA, vary with the ENSO phases and their intensities. In general, the annual risks in Florida are higher than in São Paulo, independently of the ENSO phase or intensity.

In São Paulo, the highest average annual risk of psyllid occurrence was observed during Neutral years. However, when considering the intensities of the ENSO phases, years with weak El Niño and moderate La Niña presented highest risks. In Florida, during the years of La Niña the risks were higher than Neutral and El Niño ones. When the intensity of the ENSO phases was considered, the highest average risk occurred under strong La Niña, followed by weak El Niño, weak La Niña, Neutral, moderate La Niña, and strong and moderate El Niño events.

For monthly risks of psyllids occurrence, not many differences were observed between the events intensities. For the state of São Paulo, in general, the highest risks occurred from October to December mainly in weak El Niño and strong La Niña. For Neutral events in this state, the highest risks also occurred in the same period. For the state of Florida, the highest risks for psyllids occurrence were observed, in general, from May to December in all intensities of El Niño, from March to December in all intensities of La Niña and also for the Neutral events.

Neutral years were those with the highest eradication risk in the state of São Paulo, with most of the years with this event presenting very high risk. When assessing the intensity of the phenomenon ENOS was mainly in the autumn and winter.

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6. General conclusions

This complex study allowed to achieve results of relevance for the study of HLB occurrence in citrus orchards. Based on these results, the following general conclusion were set:

a) The model based on water deficit, followed by rainfall and average air temperature between 16 to 28 °C, was the best one for estimating the number of psyllids captured per block in orange orchards in states of São Paulo, Brazil, and Florida, USA, allowing its use as an important tool to assist the orange growers in Brazil and USA in their decision-making regarding psyllid control;

b) Psyllid occurrence risk maps generated from the proposed model was able to distinguish the area with higher risk for HLB vector, which is an important tool for control planning as well as for decision making for a more rational use of chemicals for HLB management;

c) The average annual risk for psyllid occurrence was greater in Florida than in the states of São Paulo, Texas and California. These risks in the states, Florida, Texas and California, showed to be higher in the south, whereas for the state of São Paulo, Brazil, the risks were higher in the northern region of the state;

d) Over the months, in the states of Florida, Texas and California, the risks of psyllid occurrence start to increase in late spring and reach its peak in the summer months. For the state of São Paulo, the psyllid occurrence has the risks increasing from spring, with the peak occurring in the summer, decreasing gradually after that, with lower values occurring in the winter;

e) The eradication of citrus tree with symptoms of HLB is favored by the number of psyllids 18 months before the eradication, combined with an average temperature lower than 23 °C in the month of eradication. The final model of risk of eradication used these two variables in a proportion of 75% for the first and 25% for the second. For annual scale, the risk of eradication showed to be higher in the center and south of the state of São Paulo and lower in the north. When monthly risks were assessed, the higher risks occur from March to June, mainly in the center and south of the state;

f) The risk of occurrence of the psyllid in the state of São Paulo, Brazil, and Florida, USA, vary with the ENSO phases and their intensities. In general, the annual risks in Florida are higher than in São Paulo, independently of the ENSO phase or intensity. In São Paulo, the highest average annual risk of psyllid occurrence was observed during Neutral years. In Florida, during the years of La Niña the risks were higher than Neutral and El Niño ones. When the intensity of the ENSO phases was considered, the highest average risk occurred under strong La Niña, followed by weak El Niño, weak La Niña, Neutral, moderate La Niña, and strong and moderate El Niño events;

g) For monthly risks of psyllids occurrence, there is no clear difference between the events intensities. For the state of São Paulo, in general, the highest risks occurred from October to December mainly in weak El Niño and strong La Niña. For Neutral events in this state, the highest risks also occurred in the same period. For the state of Florida, the highest risks for psyllids occurrence were observed, in general, from May to December in all intensities of El Niño, from March to December in all intensities of La Niña and also for the Neutral events;

h) Neutral years were those with the highest eradication risk in the state of São Paulo, with most of the years with this event presenting very high risk. When assessing the intensity of the phenomenon, the highest risks of citrus tree eradication occur on autumn and winter.

Appendix A

Table A1. Coefficients used to spatialize the number of sprays for the different control theshold levels (CL): 1 or 2 psyllid per block and 3 or 4 psyllid per block, and the temperature for the annual period for the state of São Paulo, Brazil.

Thesholds	a	b	c	d	e	f	g	h	i	j
1 or 2 psyllid	-3488.47	-163.01	-71.30	-0.14	-3.53	-0.64	0.00	-0.24	-0.01	0.00
3 or 4 psyllid	-2906.81	-147.04	-54.99	0.14	-3.47	-0.54	0.00	0.04	-0,005	0.00
Temperature	19.21	0.66	-0.39	0.00	-	-	-	-	-	-

Table A2. Coefficients used to spatialize the number of sprays for the different control theshold levels (CL): 1 or 2 psyllid per block and 3 or 4 psyllid per block, and the temperature for the annual period for the state of Florida, USA.

Thesholds	a	b	c	d	e	f	g	h	i	j
1 or 2 psyllid	941.10	-1.45	17.68	-2.27	-1.45	-0.08	0.00	-1.00	-0.17	-0.08
3 or 4 psyllid	1052.30	6.55	23.02	-2.81	-1.51	-0.04	0.00	-0.95	-0.17	-0.09
Temperature	57.46	-0.78	0.17	0.00	-	-	-	-	-	-

Table A3. Coefficients used to spatialize the number of sprays for the different control theshold levels (CL): 1 or 2 psyllid per block and 3 or 4 psyllid per block, and the temperature for the annual period for the state of Texas, USA.

Thesholds	a	b	c	d	e	f	g	h	i	j
1 or 2 psyllid	-6811.85	-74.30	-164.64	-0.29	0.16	-0.95	0.00	-0.66	-0.01	0.00
3 or 4 psyllid	6100.55	-71.71	-150.08	-0.26	0.19	-0.87	0.00	-0.61	-0.01	0.00
Temperature	34.31	-0.73	-0.09	0.00	-	-	-	-	-	-

Table A4. Coefficients used to spatialize the number of sprays for the different control theshold levels (CL): 1 or 2 psyllid per block and 3 or 4 psyllid per block, and the temperature for the annual period for the state of California, USA.

Thesholds	a	b	c	d	e	f	g	h	i	j
1 or 2 psyllid	-3983.13	-146.62	-112.05	0.24	-0.19	-0.68	0.00	-1.36	0.00	0.00
3 or 4 psyllid	-3522.38	-120.87	-96.41	0.23	-0.09	-0.57	0.00	-1.08	0.00	0.00
Temperature	132.24	0.03	0.96	-0.01	-	-	-	-	-	-

Appendix B

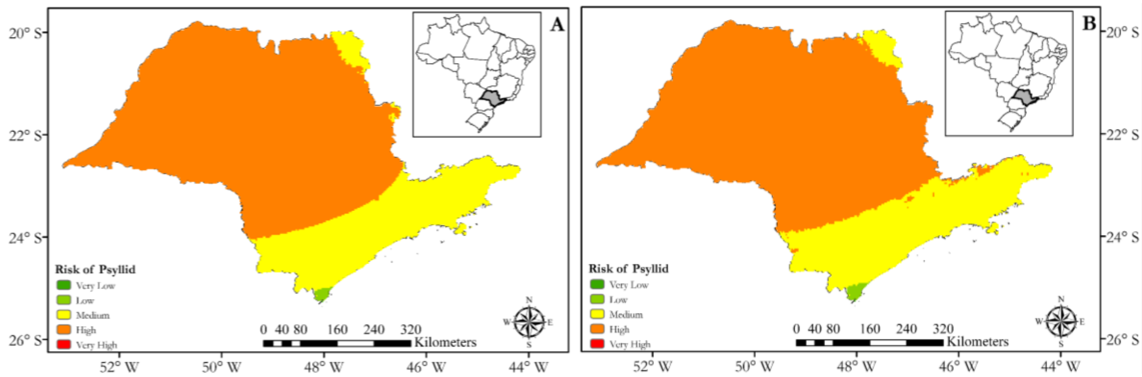

Figure B1. Average annual Asian psyllid occurrence risk in the state of São Paulo, Brazil, USA, based on the combination of the number of sprays model, considering the thresholds of 1 and 2 psyllids per block (A) and 3 and 4 psyllids per block (B).

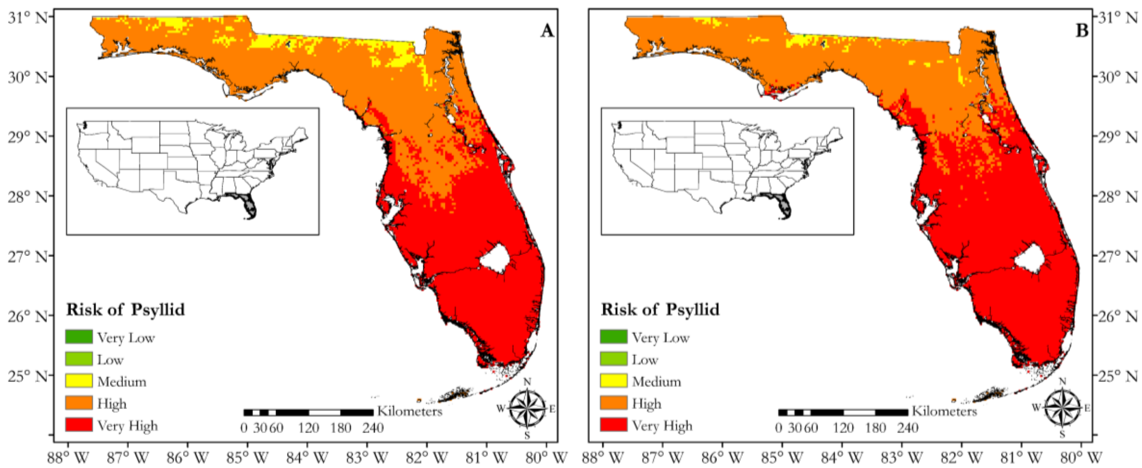

Figure B2. Average annual Asian psyllid occurrence risk in the state of Florida, USA, based on the combination of the number of sprays model, considering the thresholds of 1 and 2 psyllids per block (A) and 3 and 4 psyllids per block (B).

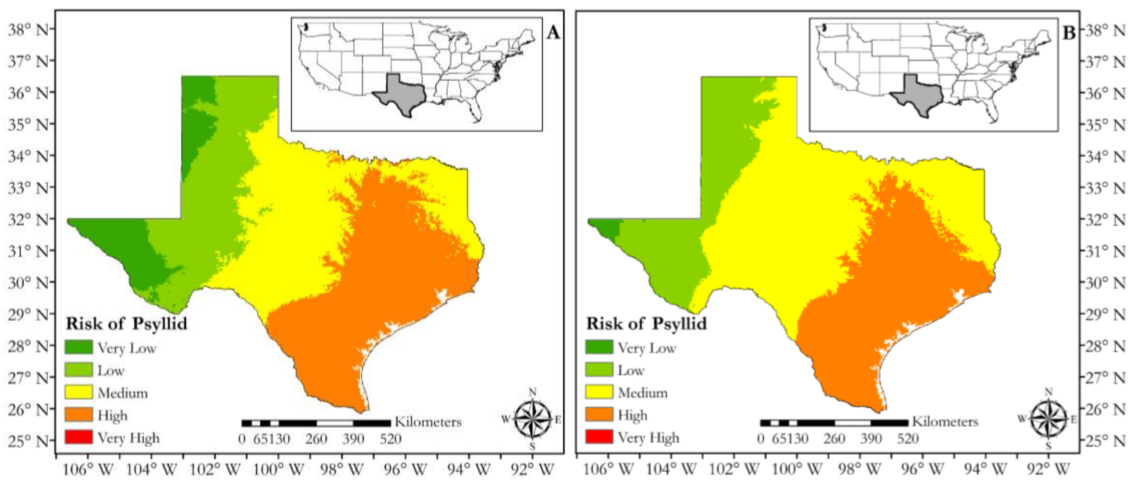

Figure B3. Average annual Asian psyllid occurrence risk in the state of Texas, USA, based on the combination of the number of sprays model, considering the thresholds of 1 and 2 psyllids per block (A) and 3 and 4 psyllids per block (B).

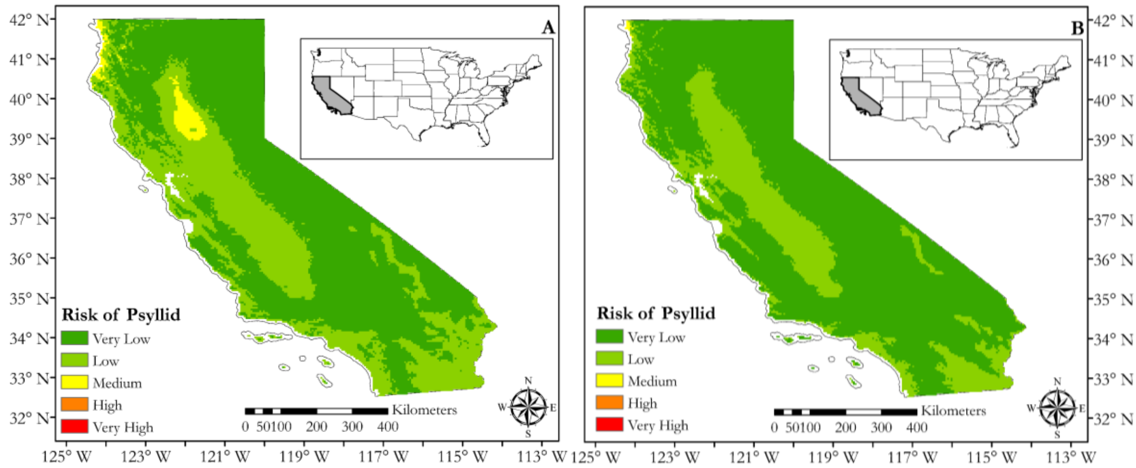

Figure B4. Average annual Asian psyllid occurrence risk in the state of California, USA, based on the combination of the number of sprays model, considering the thresholds of 1 and 2 psyllids per block (A) and 3 and 4 psyllids per block (B).

Appendix C

Table C1. Coefficients used to spatialize the number of sprays for the different control theshold levels (CL): 1 or 2 psyllid per block and 3 or 4 psyllid per block, and the temperature for the monthly period for the state of São Paulo, Brazil.

Thresholds	Months	a	b	c	d	e	f	g	h	i	j
1 or 2 psyllid	Jan	-6798.69	-247.87	-157.55	0.12	-3.55	-1.12	0.00	-1.77	0.00	0.01
	Feb	-2271.20	-149.21	-20.74	0.06	-2.63	-0.01	0.00	-0.65	0.00	0.00
	Mar	-474.56	-122.42	32.71	-0.25	-2.84	0.34	0.00	0.01	0.00	0.00
	Apr	-5359.12	-234.59	-110.26	-0.07	-4.65	-0.91	0.00	-0.65	-0.01	0.00
	May	-4575.21	-169.93	-115.16	-0.36	-4.15	-1.16	0.00	0.07	-0.01	0.00
	Jun	-2422.11	-72.28	-73.47	-0.25	-2.55	-0.86	0.00	0.56	-0.01	0.00
	Jul	-3501.50	-104.80	-99.66	-0.06	-2.90	-1.06	0.00	0.29	-0.01	0.00
	Agu	-1100.22	-174.44	26.72	-0.45	-4.94	0.07	0.00	0.80	0.00	-0.01
	Sep	291.59	-74.60	41.63	-0.14	-2.08	0.34	0.00	0.34	0.00	0.00
	Oct	2296.52	-2.62	83.77	-0.45	-2.52	0.35	0.00	2.06	-0.01	-0.01
	Nov	-2256.79	-169.11	-26.00	-0.57	-3.85	-0.27	0.00	-0.12	-0.01	-0.01
	Dec	-7301.61	-242.96	-190.53	-0.26	-3.87	-1.57	0.00	-1.52	-0.01	0.00
3 or 4 pyllid	Jan	-6284.47	-231.64	-143.64	0.13	-3.27	-0.99	0.00	-1.69	0.00	0.01
	Feb	-2649.44	-149.83	-35.01	0.15	-2.80	-0.18	0.00	-0.49	0.00	0.00
	Mar	-452.05	-115.10	30.04	-0.25	-2.63	0.31	0.00	-0.03	0.00	0.00
	Apr	-5089.69	-224.83	-103.76	-0.04	-4.52	-0.86	0.00	-0.57	-0.01	0.00
	May	-4493.29	-169.10	-111.92	-0.36	-4.06	-1.12	0.00	0.01	-0.01	0.00
	Jun	-1726.58	-44.67	-57.70	-0.24	-2.47	-0.82	0.00	1.06	-0.01	0.00
	Jul	-3372.30	-115.16	-89.11	-0.07	-2.64	-0.86	0.00	-0.13	0.00	0.00
	Agu	-583.28	-147.46	35.59	-0.46	-4.65	0.09	0.00	1.08	0.00	-0.01
	Sep	-546.98	-97.41	17.50	-0.11	-2.45	0.12	0.00	0.20	0.00	0.00
	Oct	2594.82	-3.37	96.14	-0.52	-2.47	0.48	0.00	2.03	-0.01	-0.01
	Nov	-1508.34	-145.11	-6.58	-0.59	-3.64	-0.14	0.00	0.17	-0.01	-0.01
	Dec	-8502.39	-266.74	-227.49	-0.12	-3.99	-1.84	0.00	-1.91	-0.01	0.00
Temperature	Jan	9.08	0.22	-0.43	0.00	-	-	-	-	-	-
	Feb	11.93	0.21	-0.38	0.00	-	-	-	-	-	-
	Mar	12.99	0.37	-0.41	0.00	-	-	-	-	-	-
	Apr	15.86	0.55	-0.41	0.00	-	-	-	-	-	-
	May	19.38	0.66	-0.33	0.00	-	-	-	-	-	-
	Jun	19.27	0.79	-0.37	0.00	-	-	-	-	-	-
	Jul	20.93	0.90	-0.39	0.00	-	-	-	-	-	-
	Agu	21.24	1.01	-0.46	0.00	-	-	-	-	-	-
	Sep	29.23	1.17	-0.40	0.00	-	-	-	-	-	-
	Oct	25.65	1.02	-0.43	0.00	-	-	-	-	-	-
	Nov	17.88	0.67	-0.44	0.00	-	-	-	-	-	-
	Dec	11.02	0.38	-0.46	0.00	-	-	-	-	-	-

Table C2. Coefficients used to spatialize the number of sprays for the different control theshold levels (CL): 1 or 2 psyllid per block and 3 or 4 psyllid per block, and the temperature for the monthly period for the State of Florida, USA.

Thresholds	Months	a	b	d	c	e	f	g	h	i	j
1 or 2 psyllid	Jan	390.25	61.82	22.52	-3.59	-2.50	-0.03	0.00	-0.85	-0.24	-0.12
	Feb	-1349.69	176.52	18.84	-9.67	-3.28	0.11	0.00	0.07	-0.10	-0.15
	Mar	1959.87	233.22	117.64	-4.09	-3.59	0.78	0.00	0.50	-0.27	-0.14
	Apr	2588.59	62.20	78.80	2.28	-2.11	0.36	0.00	-0.64	-0.09	0.00
	May	693.55	-81.75	-14.10	1.59	-0.04	-0.27	0.00	-1.04	-0.08	-0.01
	Jun	1443.31	-9.36	29.47	1.80	0.30	0.19	0.00	0.09	-0.05	0.00
	Jul	-1670.24	-3.48	-43.27	-1.57	-0.18	-0.29	0.00	-0.18	-0.02	-0.03
	Agu	79.39	108.47	38.78	-6.75	-0.93	0.34	0.00	0.63	-0.02	-0.08
	Sep	3829.69	-159.51	35.41	-1.99	-0.40	-0.20	0.00	-2.30	-0.06	-0.04
	Oct	-359.09	-357.93	-134.19	-1.39	-2.56	-1.89	0.00	-6.18	-0.11	-0.05
	Nov	-2653.87	-224.33	-143.84	-3.72	-2.30	-1.62	0.00	-4.34	-0.25	-0.13
	Dec	1949.63	-20.81	34.39	-1.46	-2.36	-0.13	0.00	-1.86	-0.37	-0.14
3 or 4 pyllid	Jan	458.31	15.25	7.62	-3.65	-2.50	-0.22	0.00	-1.42	-0.21	-0.11
	Feb	-751.13	166.54	30.43	-7.90	-3.26	0.16	0.00	-0.05	-0.08	-0.12
	Mar	1999.23	234.14	118.41	-5.64	-3.57	0.78	0.00	0.54	-0.23	-0.15
	Apr	2236.31	89.91	80.65	3.51	-1.87	0.46	0.00	-0.14	-0.14	0.00
	May	1571.92	-116.75	-5.14	2.63	-0.19	-0.31	0.00	-1.57	-0.12	-0.01
	Jun	954.95	-80.86	-7.99	-0.24	0.11	-0.22	0.00	-0.92	-0.03	-0.01
	Jul	-1466.63	72.77	-11.19	-0.36	0.10	0.11	0.00	0.95	-0.04	-0.02
	Agu	-906.09	59.71	-1.96	-6.36	-1.07	-0.03	0.00	-0.08	-0.03	-0.08
	Sep	5193.59	-175.63	62.85	-3.46	-0.06	-0.04	0.00	-2.28	-0.09	-0.07
	Oct	-2291.72	-387.45	-190.07	0.34	-2.54	-2.28	0.01	-6.53	-0.15	-0.04
	Nov	-1379.55	-197.67	-104.15	-4.73	-2.10	-1.30	0.00	-3.85	-0.21	-0.13
	Dec	1336.35	32.89	37.94	-1.96	-2.77	-0.04	0.00	-1.48	-0.33	-0.13
Temperature	Jan	82.55	-1.49	0.32	0.00	-	-	-	-	-	-
	Feb	80.52	-1.36	0.32	0.00	-	-	-	-	-	-
	Mar	64.85	-1.01	0.22	0.01	-	-	-	-	-	-
	Apr	55.18	-0.74	0.16	0.00	-	-	-	-	-	-
	May	42.62	-0.42	0.08	0.00	-	-	-	-	-	-
	Jun	31.95	-0.15	0.01	0.00	-	-	-	-	-	-
	Jul	29.73	-0.07	0.00	0.00	-	-	-	-	-	-
	Agu	32.76	-0.16	0.01	-0.01	-	-	-	-	-	-
	Sep	44.22	-0.41	0.07	-0.01	-	-	-	-	-	-
	Oct	65.28	-0.89	0.21	-0.01	-	-	-	-	-	-
	Nov	77.97	-1.22	0.30	-0.01	-	-	-	-	-	-
	Dec	83.28	-1.48	0.31	0.00	-	-	-	-	-	-

Table C3 Coefficients used to spatialize the number of sprays for the different control theshold levels (CL): 1 or 2 psyllid per block and 3 or 4 psyllid per block, and the temperature for the monthly periodfor the State of Texas, USA.

Thresholds	Months	a	b	d	c	e	f	g	h	i	j
1 or 2 psyllid	**Jan**	643.71	-207.03	-53.46	-0.18	1.16	-0.49	0.00	-1.35	-0.01	0.00
	Feb	-862.32	-105.96	-50.95	-0.08	1.07	-0.31	0.00	-0.37	0.00	0.00
	Mar	-10618.17	-5.83	-212.88	0.18	0.03	-1.04	0.00	0.01	0.00	0.00
	Apr	-22628.27	-42.95	-471.00	-0.14	-1.11	-2.55	0.00	-1.14	-0.01	0.00
	May	-11887.21	-37.21	-255.83	-0.18	-0.20	-1.39	0.00	-0.53	0.00	0.00
	Jun	-7819.44	-39.43	-175.54	-0.40	-0.15	-0.99	0.00	-0.52	0.00	-0.01
	Jul	-9708.65	-39.84	-217.59	-0.93	-0.46	-1.26	0.00	-0.74	-0.01	-0.01
	Agu	-5534.06	-56.42	-143.51	-1.27	-0.07	-0.90	0.00	-0.65	0.00	-0.02
	Sep	-1197.55	-61.18	-52.28	-0.71	0.03	-0.41	0.00	-0.63	0.00	-0.01
	Oct	-4456.33	3.33	-91.60	-0.23	0.11	-0.45	0.00	0.09	0.00	0.00
	Nov	-13276.93	34.06	-261.59	-0.24	-0.11	-1.29	0.00	0.28	-0.01	0.00
	Dec	-9736.46	-102.33	-230.83	-0.23	0.27	-1.29	0.00	-0.82	0.00	0.00
3 or 4 pyllid	**Jan**	857.17	-193.50	-44.69	-0.14	1.13	-0.42	0.00	-1.23	-0.01	0.00
	Feb	-890.44	-109.68	-52.98	-0.11	1.08	-0.33	0.00	-0.40	0.00	0.00
	Mar	-10601.23	5.67	-208.73	0.19	-0.05	-1.01	0.00	0.08	0.00	0.00
	Apr	-20872.26	-59.83	-440.20	-0.09	-0.99	-2.41	0.00	-1.24	-0.01	0.00
	May	-12624.89	-54.02	-276.57	-0.21	-0.21	-1.53	0.00	-0.71	-0.01	0.00
	Jun	-9566.04	-7.88	-201.12	-0.46	-0.23	-1.08	0.00	-0.24	0.00	-0.01
	Jul	-9534.32	-57.36	-220.27	-0.99	-0.45	-1.31	0.00	-0.91	-0.01	-0.01
	Agu	-6783.99	-37.32	-163.19	-1.38	0.02	-0.96	0.00	-0.40	0.00	-0.02
	Sep	-964.83	-69.30	-50.23	-0.70	-0.04	-0.42	0.00	-0.75	0.00	-0.01
	Oct	-4754.27	-1.16	-99.06	-0.25	0.13	-0.50	0.00	0.06	0.00	0.00
	Nov	-12799.06	40.45	-249.63	-0.21	-0.12	-1.22	0.00	0.33	-0.01	0.00
	Dec	-9205.16	-111.27	-222.94	-0.23	0.33	-1.26	0.00	-0.88	0.00	0.00
Temperature	**Jan**	54.74	-1.15	0.10	0.00	-	-	-	-	-	-
	Feb	49.76	-1.17	0.02	0.00	-	-	-	-	-	-
	Mar	40.94	-1.00	-0.06	0.00	-	-	-	-	-	-
	Apr	29.99	-0.86	-0.17	0.00	-	-	-	-	-	-
	May	21.30	-0.66	-0.24	0.00	-	-	-	-	-	-
	Jun	11.30	-0.35	-0.28	0.00	-	-	-	-	-	-
	Jul	4.64	-0.04	0.27	0.00	-	-	-	-	-	-
	Agu	11.17	-0.12	0.23	0.00	-	-	-	-	-	-
	Sep	29.59	-0.43	-0.10	0.00	-	-	-	-	-	-
	Oct	37.60	-0.80	-0.08	0.00	-	-	-	-	-	-
	Nov	54.98	-1.01	0.09	0.00	-	-	-	-	-	-
	Dec	66.76	-1.19	0.21	0.00	-	-	-	-	-	-

Table C4. Coefficients used to spatialize the number of sprays for the different control theshold levels (CL): 1 or 2 psyllid per block and 3 or 4 psyllid per block, and the temperature for the monthly period for the State of California, USA.

Thresholds	Months	a	b	d	c	e	f	g	h	i	j
1 or 2 psyllid	Jan	-1979.83	-52.31	-49.17	0.04	0.11	-0.26	0.00	-0.35	0.00	0.00
	Feb	858.59	-31.10	3.72	-0.08	0.17	-0.01	0.00	-0.15	0.00	0.00
	Mar	7897.82	-8.00	125.18	-0.35	0.31	0.53	0.00	0.13	0.00	0.00
	Apr	-569.83	-43.83	-29.64	-0.39	-0.25	-0.23	0.00	-0.53	0.00	0.00
	May	-17695.98	-87.22	-327.12	-0.27	-0.46	-1.56	0.00	-1.08	-0.01	0.00
	Jun	-15289.85	-129.17	-296.82	0.00	-0.40	-1.48	0.00	-1.44	-0.01	0.00
	Jul	-6980.62	-205.55	-176.23	0.49	-0.08	-1.01	0.00	-1.82	0.00	0.00
	Agu	-10289.75	-421.44	-294.46	1.61	-0.84	-1.81	0.00	-4.00	0.01	0.02
	Sep	-1148.54	-260.04	-94.31	1.32	-0.25	-0.73	0.00	-2.31	0.01	0.01
	Oct	8290.97	-56.17	122.87	0.25	0.03	0.44	0.00	-0.49	-0.01	0.00
	Nov	3372.68	71.54	77.23	-0.37	0.65	0.47	0.00	0.98	-0.01	-0.01
	Dec	-1259.28	-14.98	-26.21	-0.12	0.75	-0.05	0.00	0.36	0.00	0.00
3 or 4 pyllid	Jan	-1953.37	-52.59	-48.77	0.04	0.11	-0.26	0.00	-0.36	0.00	0.00
	Feb	544.22	-31.29	-1.46	-0.07	0.14	-0.03	0.00	-0.17	0.00	0.00
	Mar	7626.63	0.31	123.48	-0.34	0.34	0.53	0.00	0.22	0.00	0.00
	Apr	1498.59	-27.25	10.27	-0.41	-0.17	-0.04	0.00	-0.34	0.00	0.00
	May	-16865.85	-81.82	-311.51	-0.24	-0.46	-1.49	0.00	-1.03	-0.01	0.00
	Jun	-14450.16	-110.30	-276.99	-0.01	-0.39	-1.37	0.00	-1.28	-0.01	0.00
	Jul	-6830.86	-182.76	-167.36	0.37	0.10	-0.93	0.00	-1.53	0.00	0.00
	Agu	-10040.23	-406.78	-285.69	1.58	-0.89	-1.76	0.00	-3.90	0.01	0.02
	Sep	-2047.95	-264.44	-110.66	1.36	-0.22	-0.80	0.00	-2.33	0.01	0.01
	Oct	9966.82	-38.16	155.98	0.18	0.09	0.60	0.00	-0.31	-0.01	0.00
	Nov	1984.97	62.42	51.26	-0.37	0.48	0.33	0.00	0.80	-0.01	-0.01
	Dec	-620.45	-2.54	-11.82	-0.13	0.75	0.02	0.00	0.47	0.00	0.00
Temperature	Jan	28.69	-0.85	-0.11	0.00	-	-	-	-	-	-
	Feb	60.84	-0.49	0.25	-0.01	-	-	-	-	-	-
	Mar	104.25	-0.17	0.70	-0.01	-	-	-	-	-	-
	Apr	146.75	0.13	1.12	-0.01	-	-	-	-	-	-
	May	190.37	0.51	1.57	-0.01	-	-	-	-	-	-
	Jun	227.55	0.81	1.94	-0.01	-	-	-	-	-	-
	Jul	237.25	1.00	2.06	-0.01	-	-	-	-	-	-
	Agu	222.74	0.76	1.87	-0.01	-	-	-	-	-	-
	Sep	171.80	0.35	1.33	-0.01	-	-	-	-	-	-
	Oct	107.65	-0.15	0.68	-0.01	-	-	-	-	-	-
	Nov	62.29	-0.66	0.20	-0.01	-	-	-	-	-	-
	Dec	22.93	-0.87	-0.16	0.00	-	-	-	-	-	-

Appendix D

(Continue)

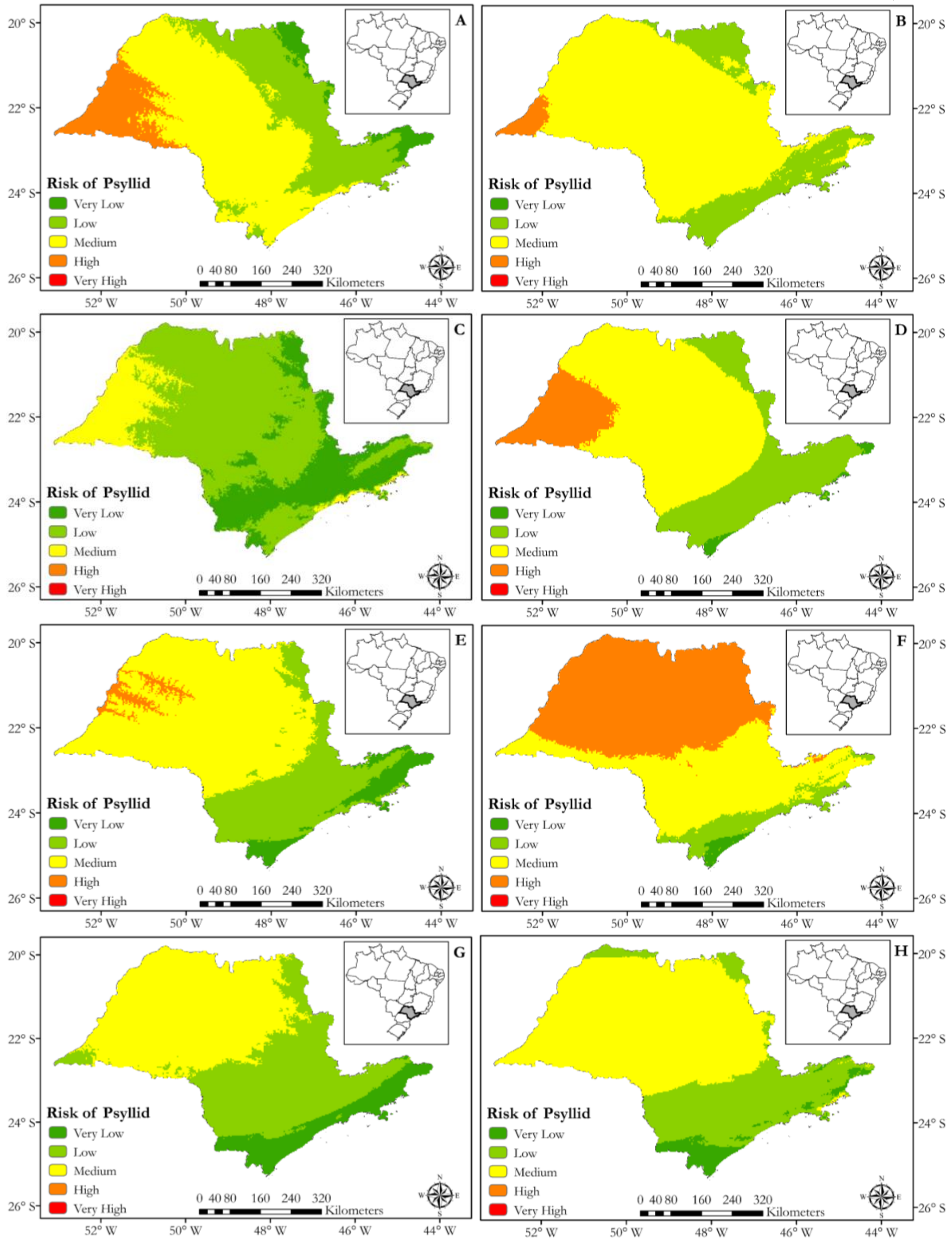

Figure D1. Average monthly Asian psyllid occurrence risk in the state of São Paulo, Brazil, based on the number of sprays model, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

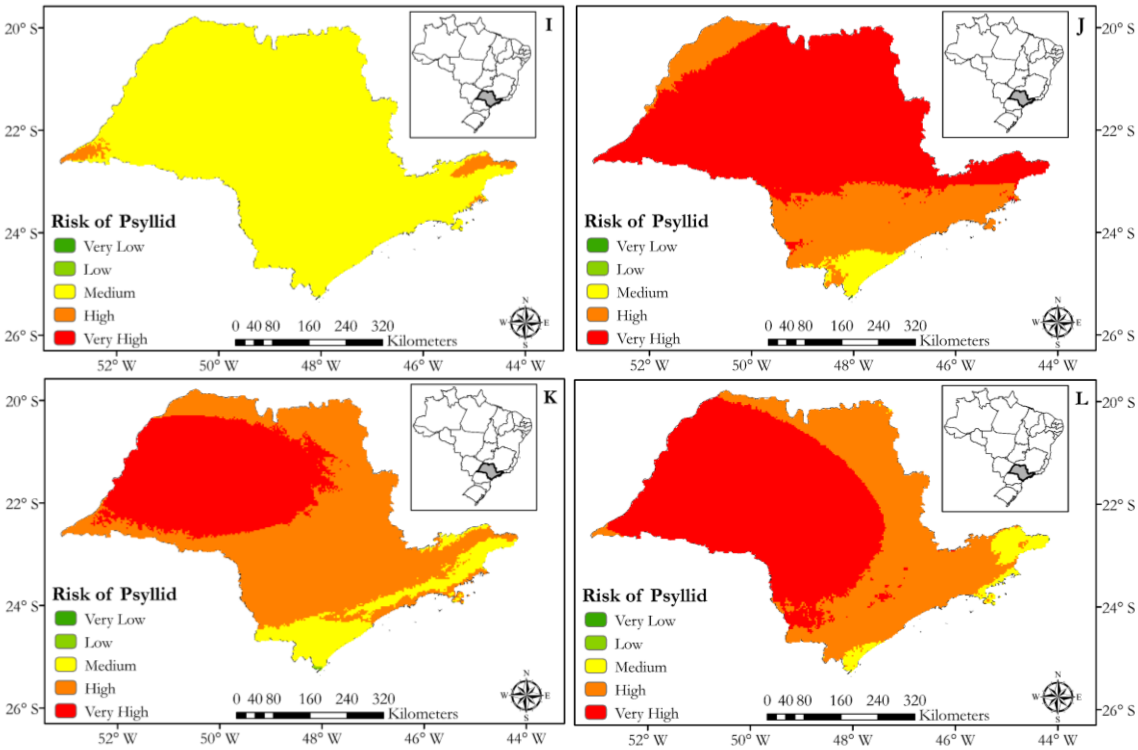

Figure D1. Average monthly Asian psyllid occurrence risk in the state of São Paulo, Brazil, based on the number of sprays model, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

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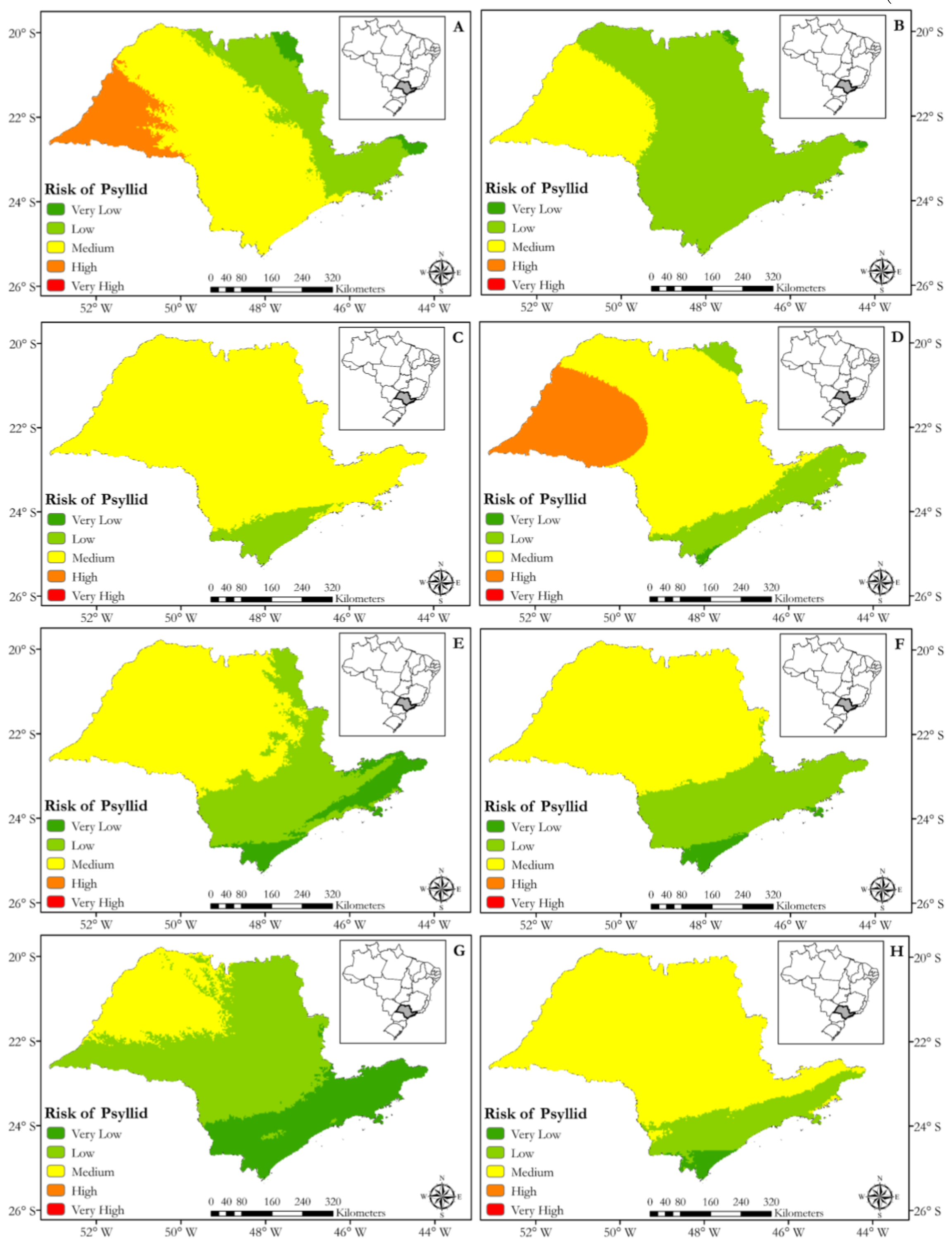

Figure D2. Average monthly Asian psyllid occurrence risk in the state of São Paulo, Brazil, based on the number of sprays model, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

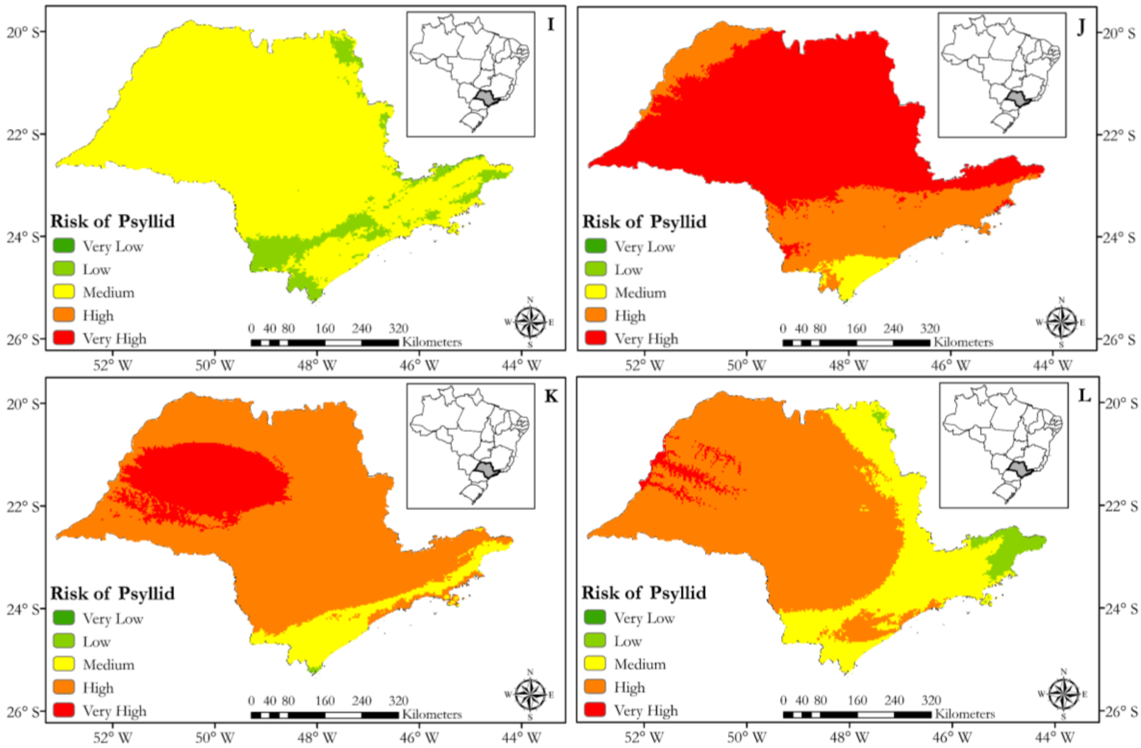

Figure D2. Average monthly Asian psyllid occurrence risk in the state of São Paulo, Brazil, based on the number of sprays model, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

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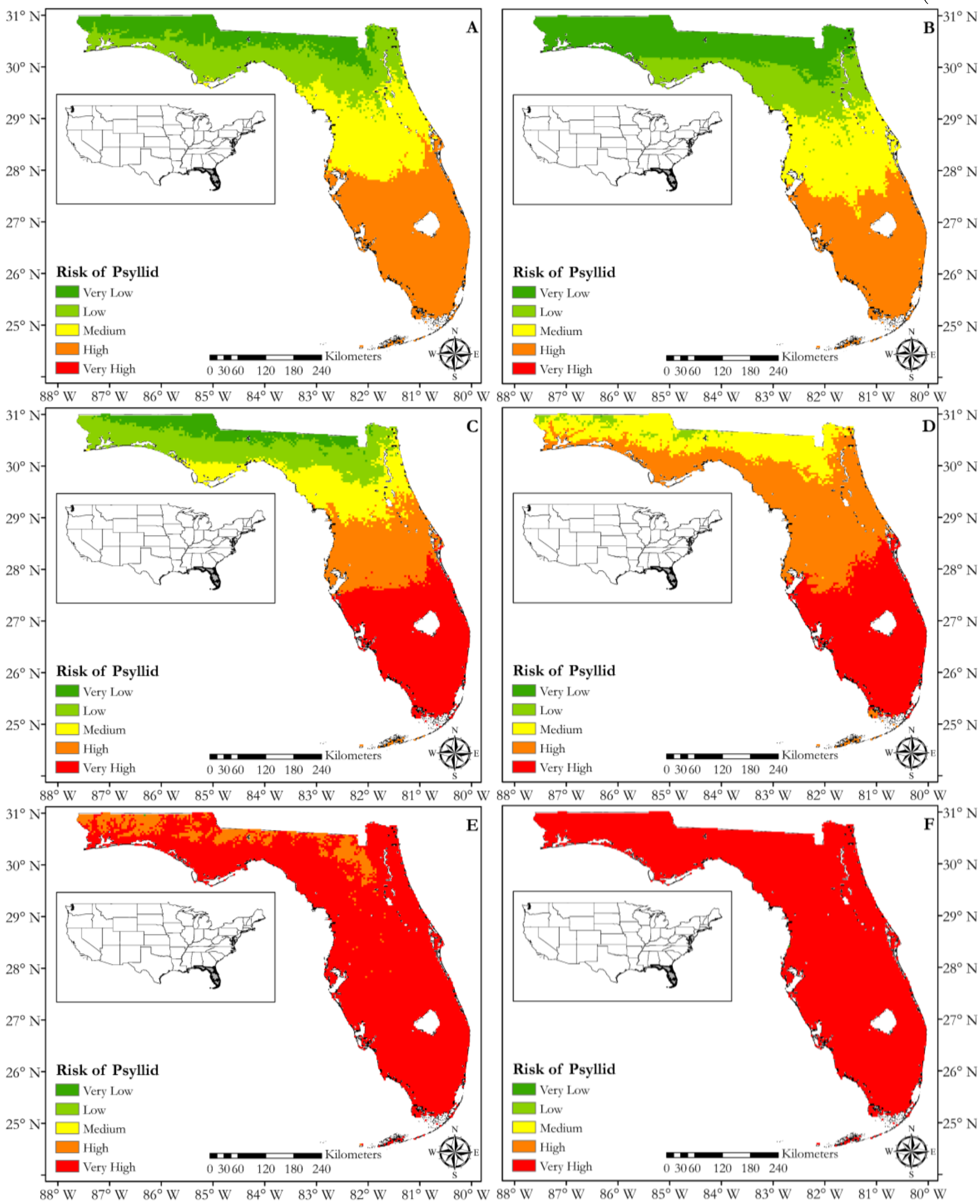

Figure D3. Average monthly Asian psyllid occurrence risk in the state of Florida, USA, based on the number of sprays model, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

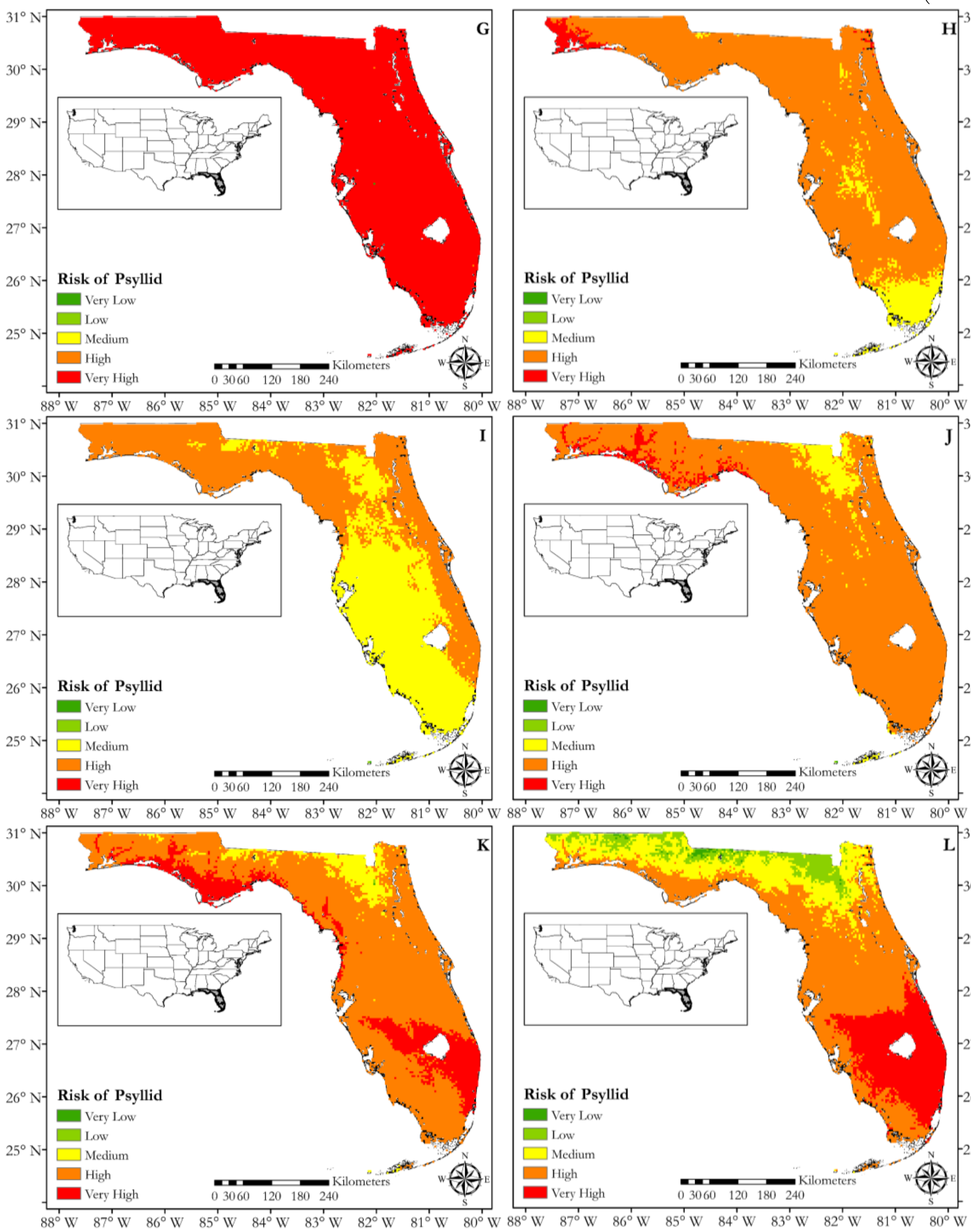

Figure D3. Average monthly Asian psyllid occurrence risk in the state of Florida, USA, based on the number of sprays model, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

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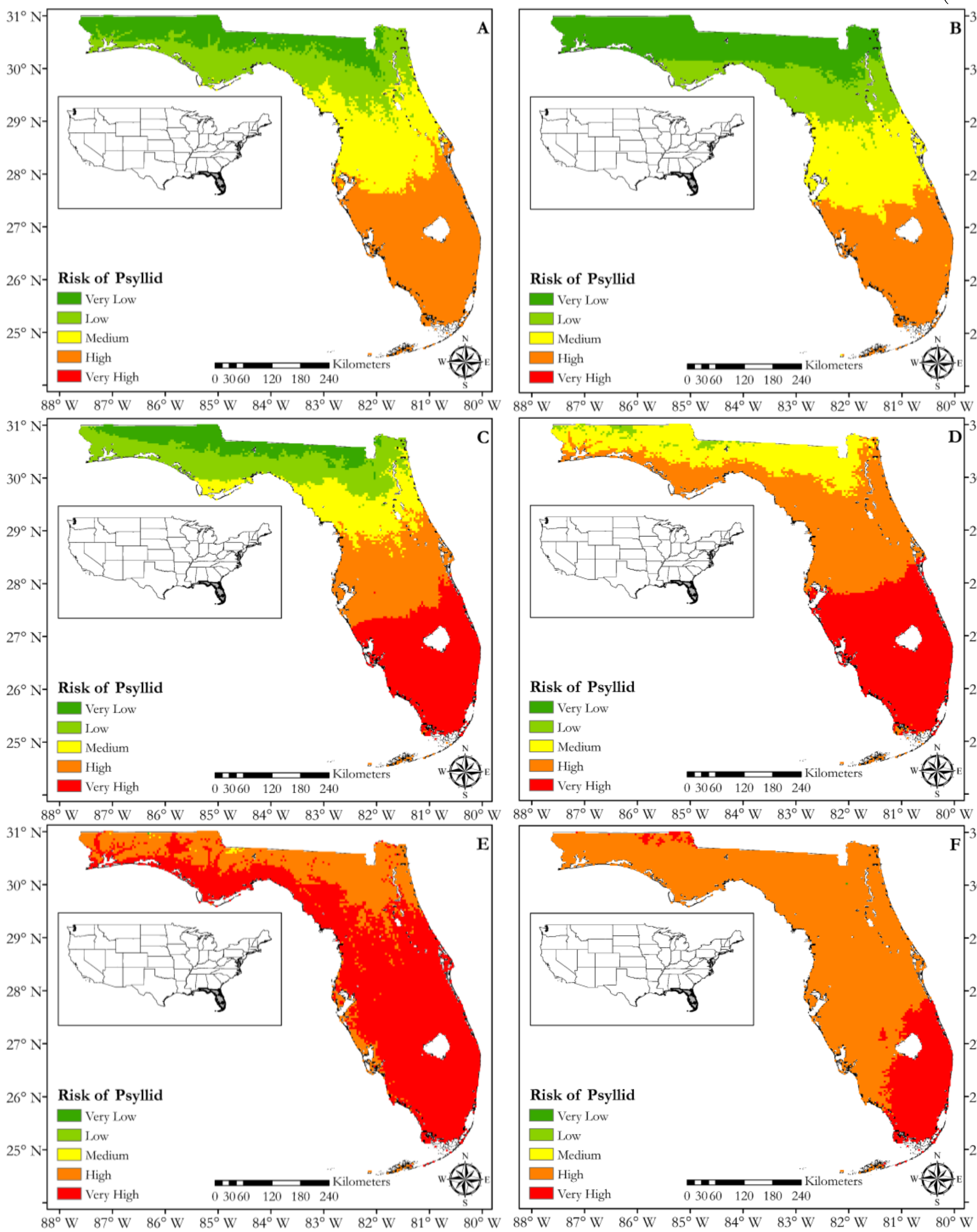

Figure D4. M Average monthly Asian psyllid occurrence risk in the state of Florida, USA, based on the number of sprays model, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

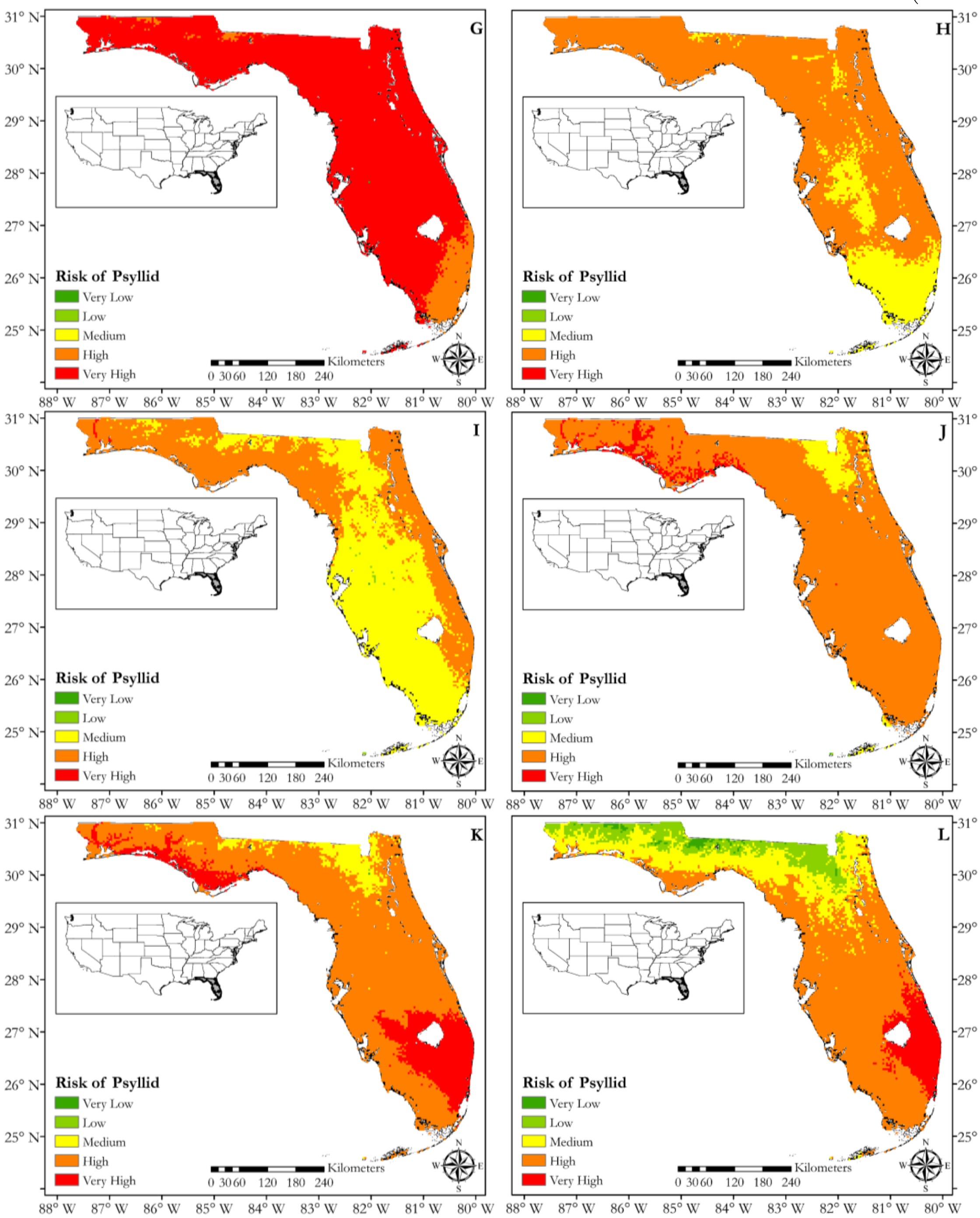

Figure D4. Average monthly Asian psyllid occurrence risk in the state of Florida, USA, based on the number of sprays model, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

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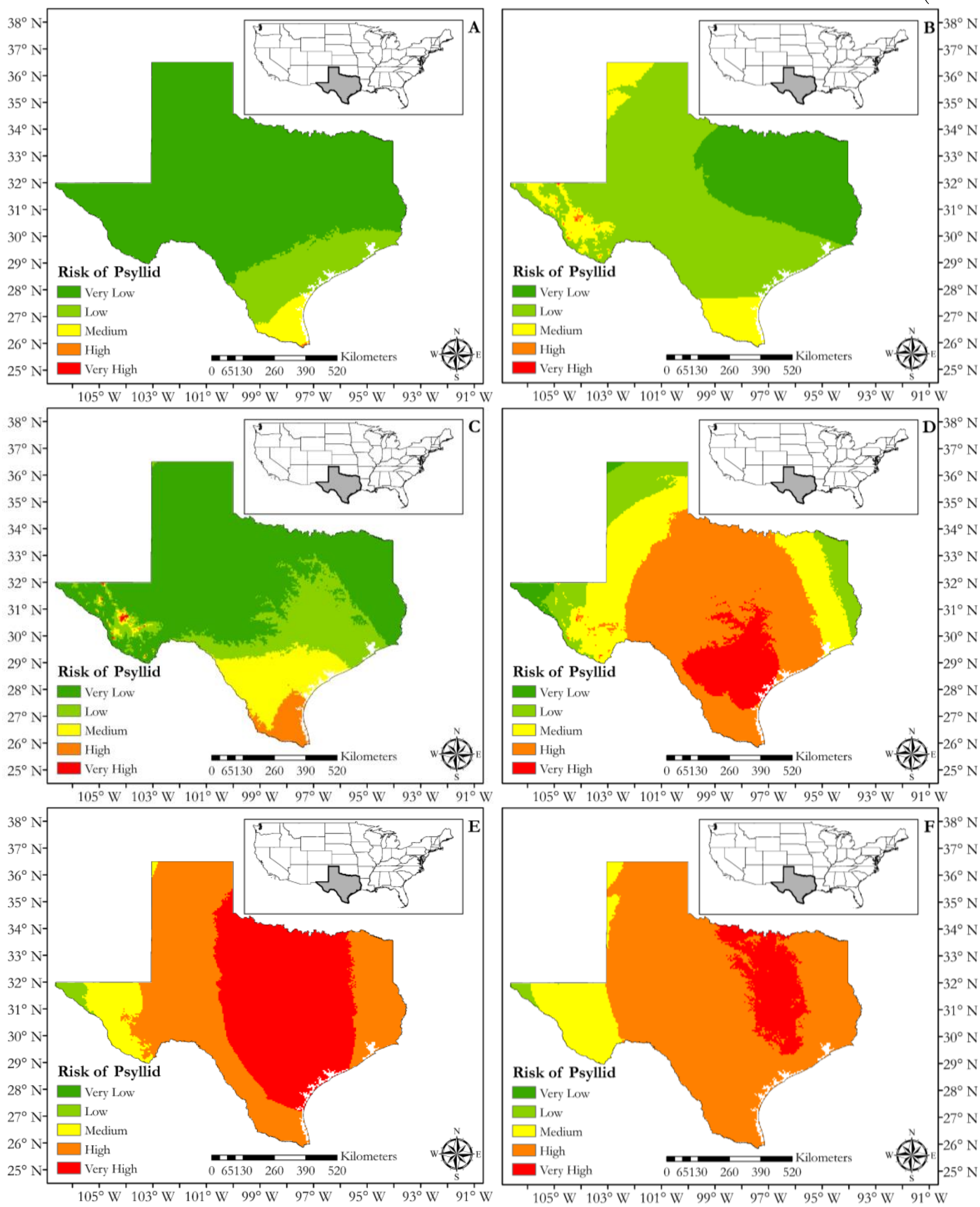

Figure D5. Average monthly Asian psyllid occurrence risk in the state of Texas, USA, based on the number of sprays model, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

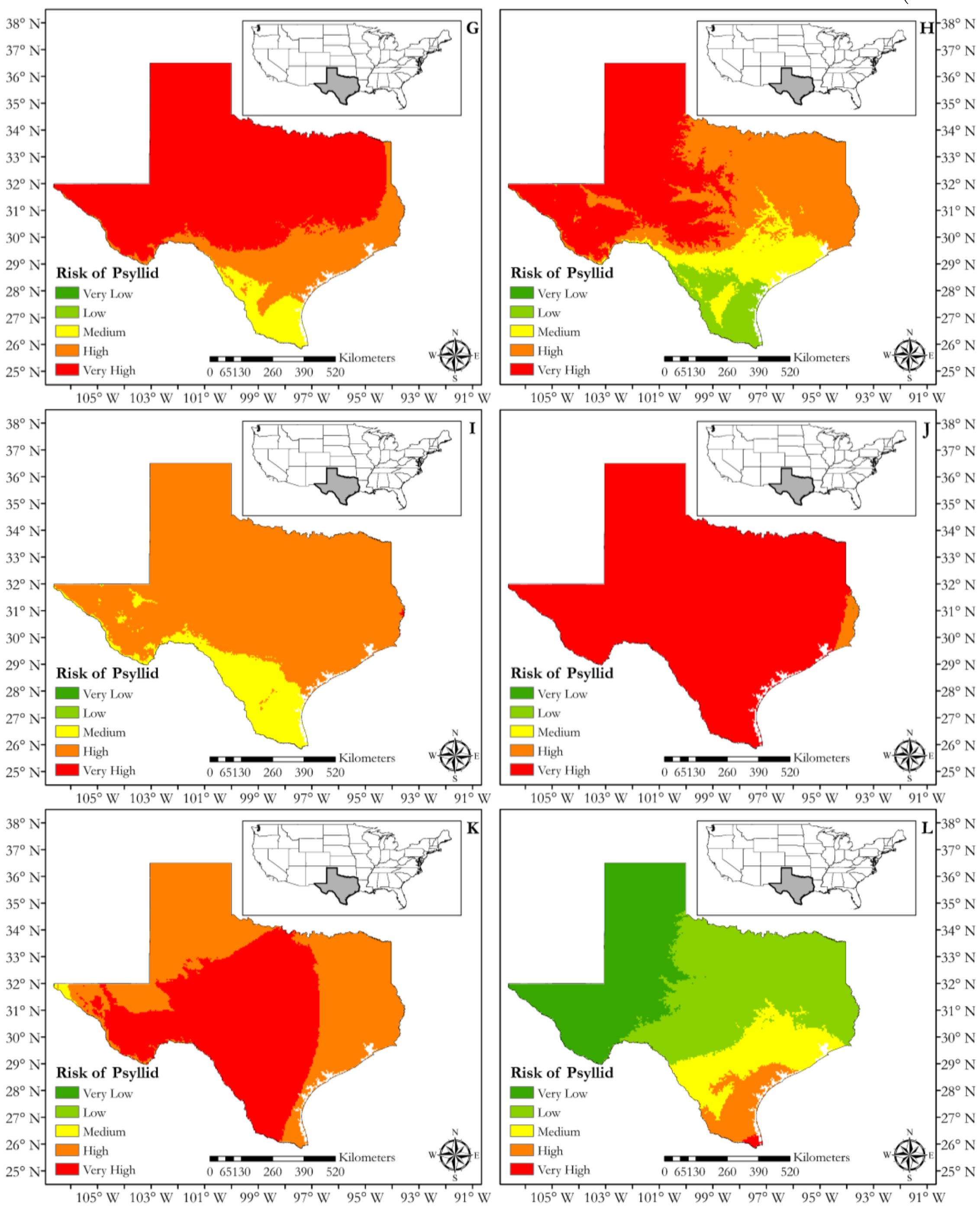

Figure D5. Average monthly Asian psyllid occurrence risk in the state of Texas, USA, based on the number of sprays model, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

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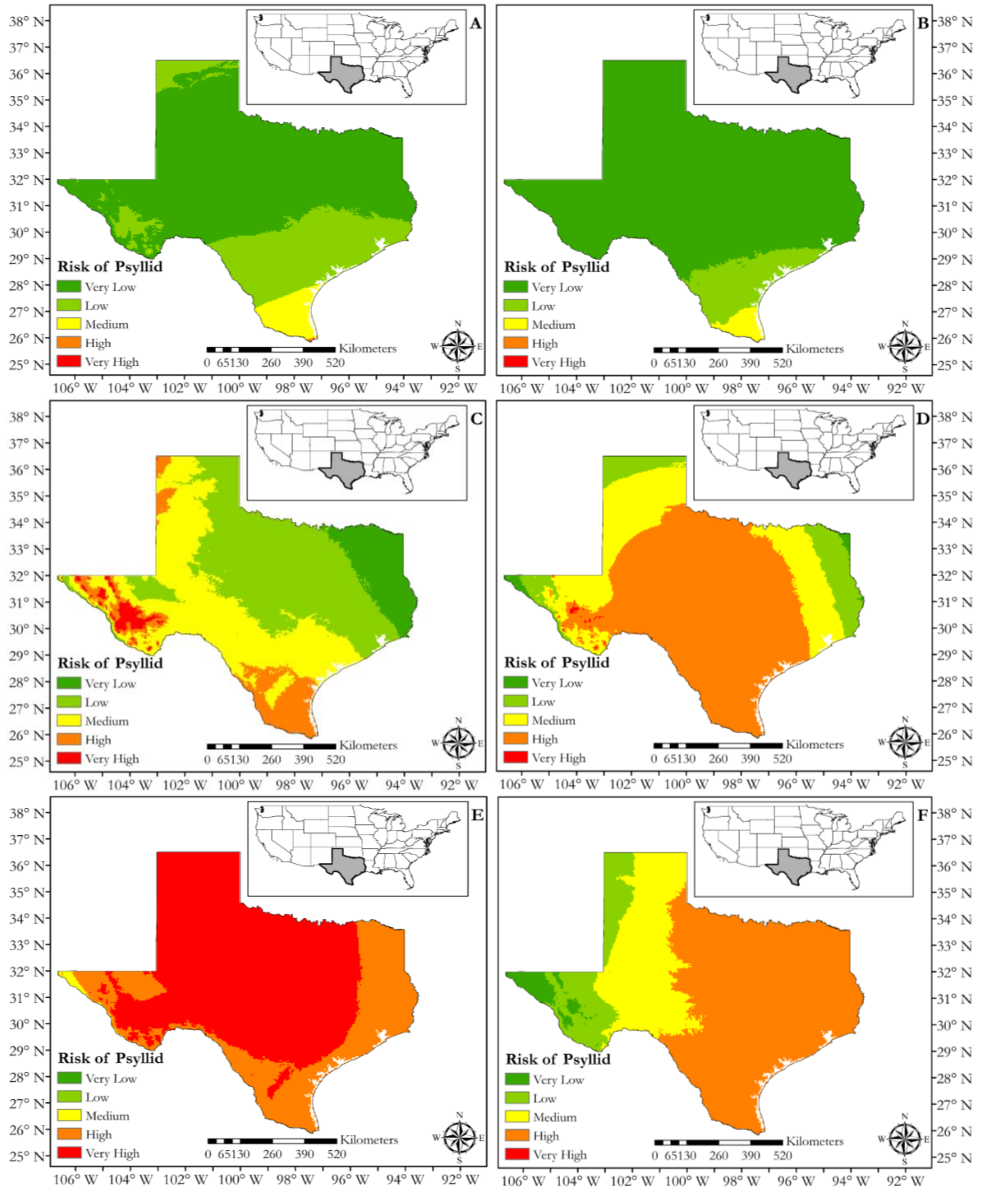

Figure D6. Average monthly Asian psyllid occurrence risk in the state of Texas, USA, based on the number of sprays model, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

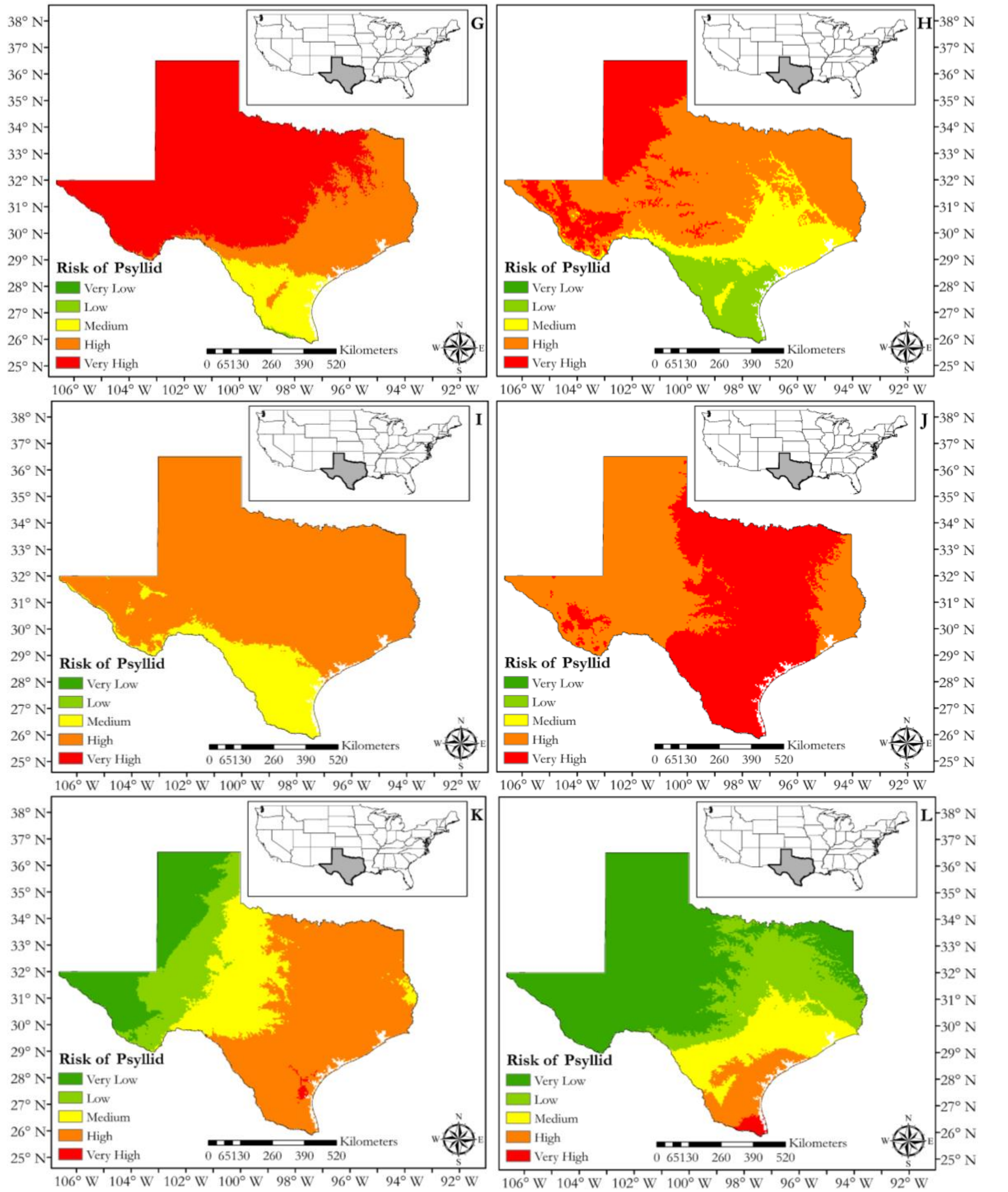

Figure D6. Average monthly Asian psyllid occurrence risk in the state of Texas, USA, based on the number of sprays model, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

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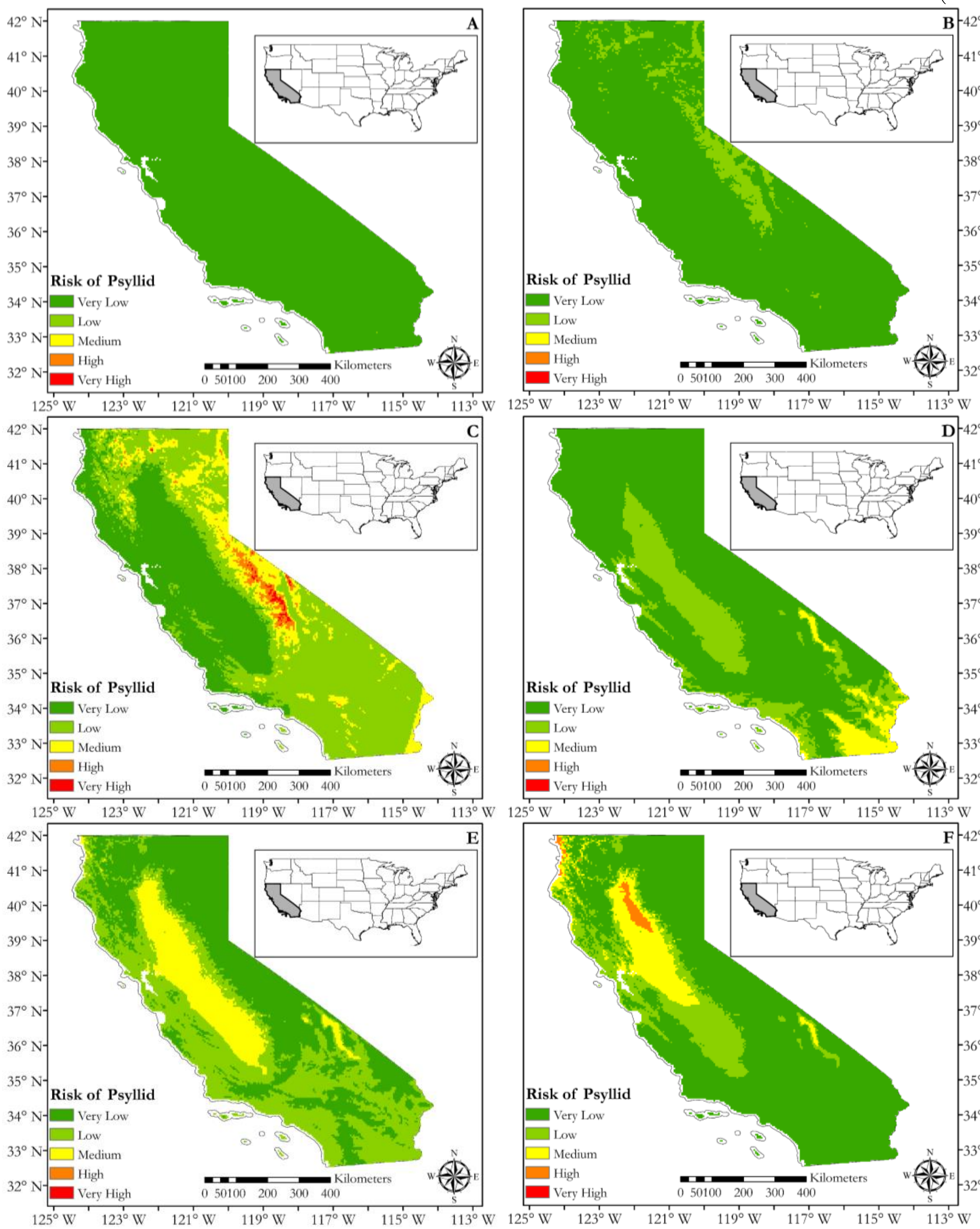

Figure D7. Average monthly Asian psyllid occurrence risk in the state of California, USA, based on the number of sprays model, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

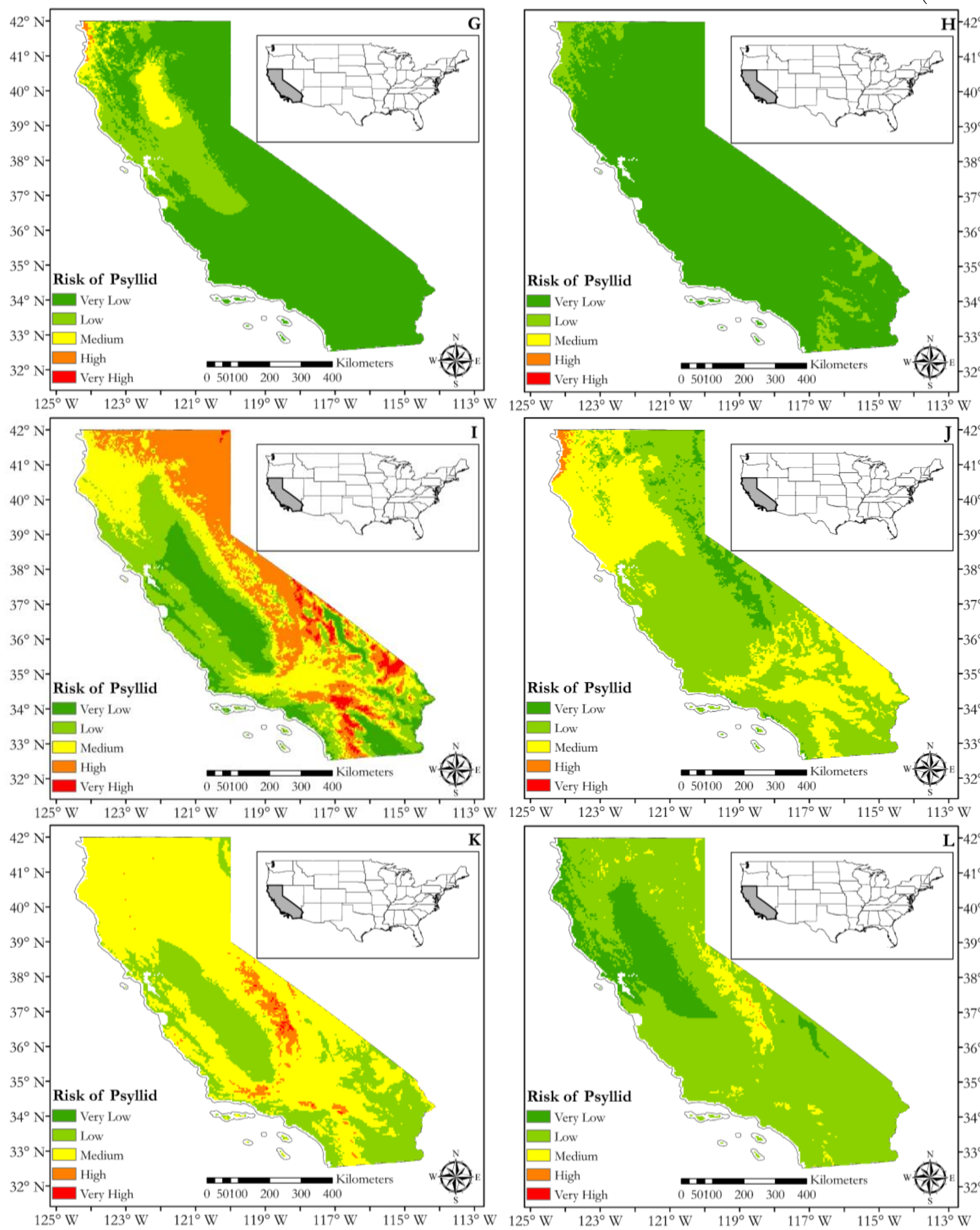

Figure D7. Average monthly Asian psyllid occurrence risk in the state of California, USA, based on the number of sprays model, considering the threshold of 1 and 2 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

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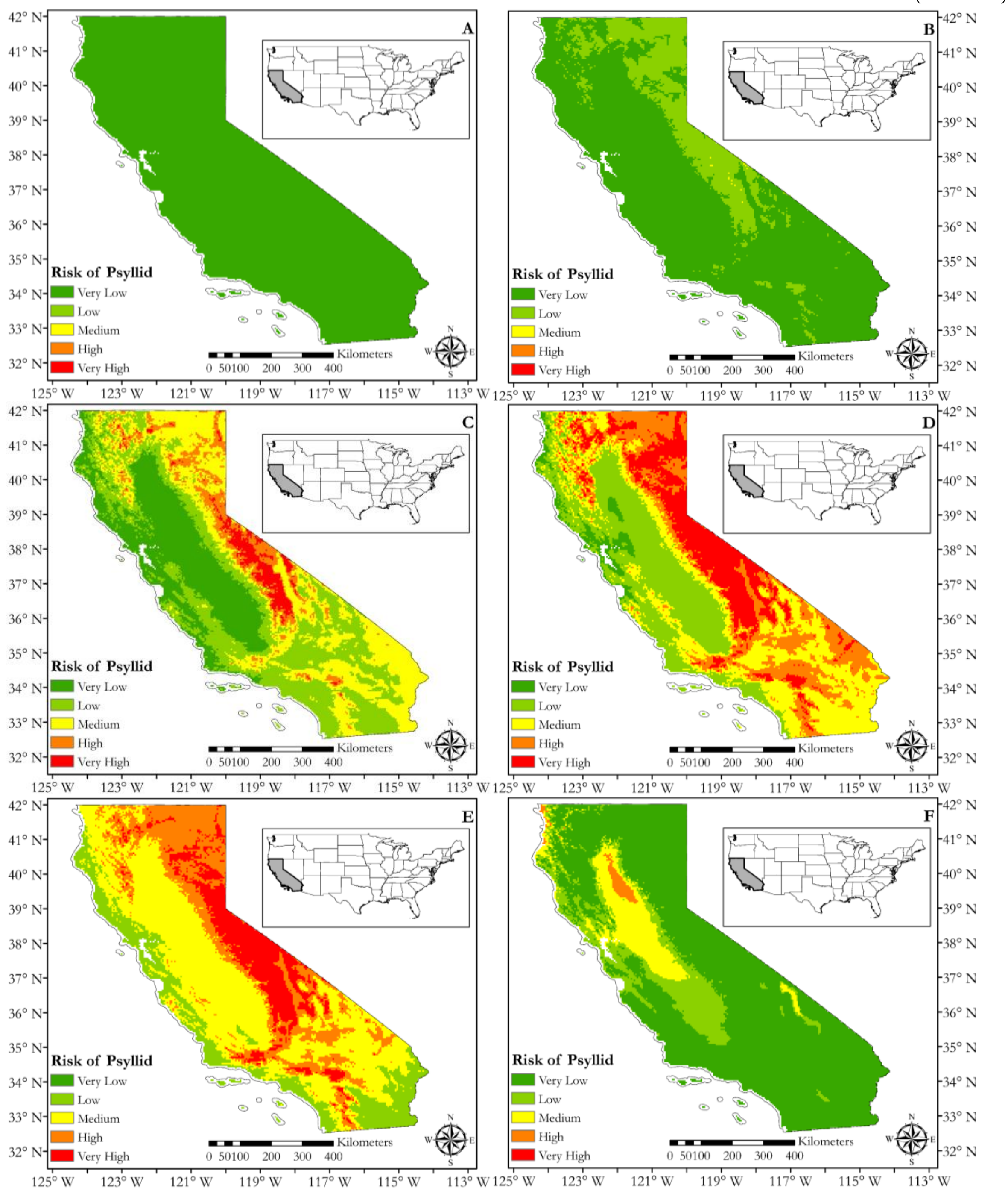

Figure D8. Average monthly Asian psyllid occurrence risk in the state of California, USA, based on the number of sprays model, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

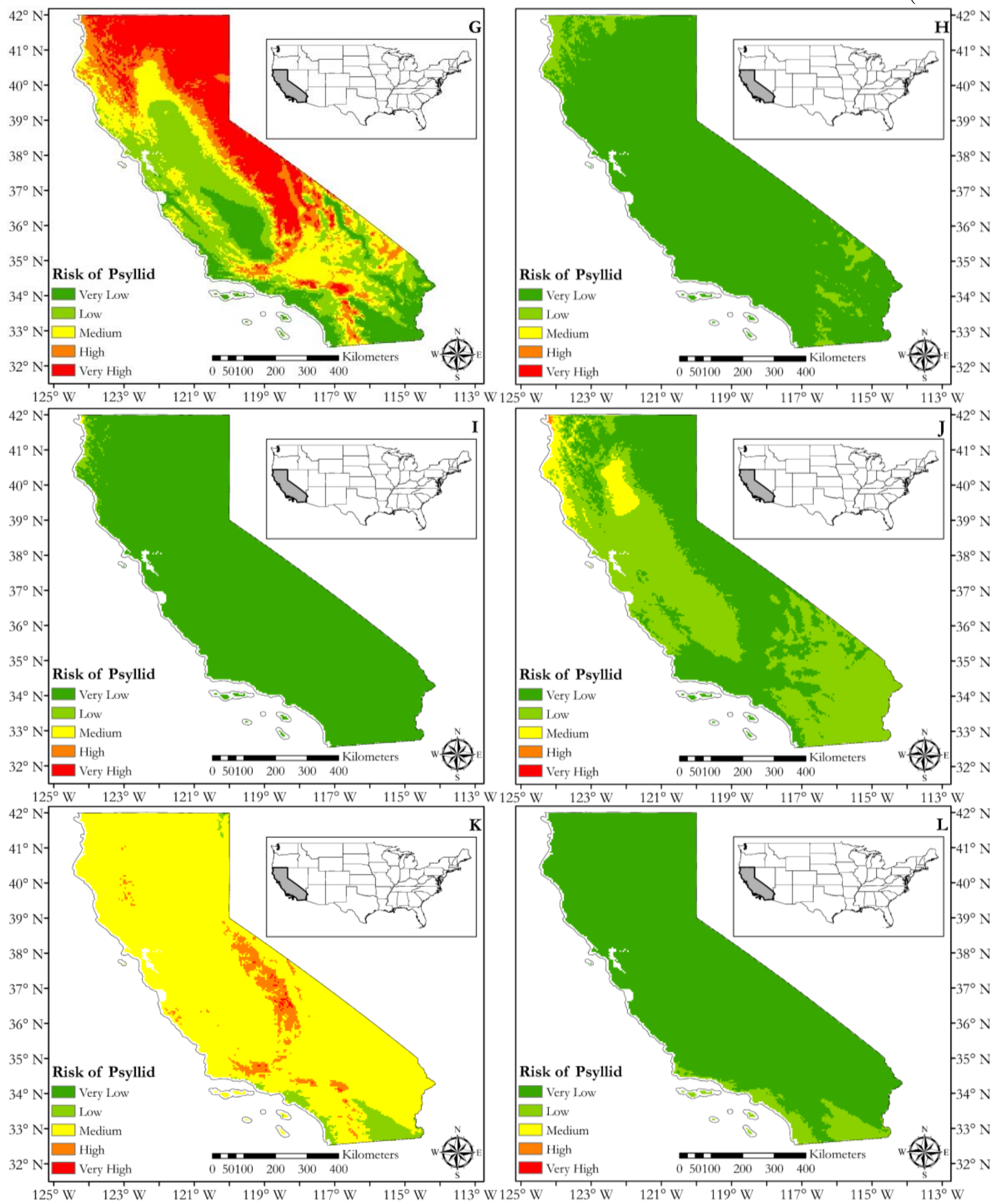

Figure D8. Average monthly Asian psyllid occurrence risk in the state of California, USA, based on the number of sprays model, considering the threshold of 3 and 4 psyllids per block in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

Appendix E

Table E1. Coefficients used to spatialize the relative eradication for the: n number of psyllid combinated with number of psyllid generation (NPG) based in degree-days and number day with temperature below that 23 °C for the annual period for the state of São Paulo, Brazil.

Models	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**
N° psyllid+NPG	-81130.54	-3419.81	-1774.94	-1.62	-59.78	-12.77	0.0001	-18.65	-0.11	0.03
N° dias Temp< 23 °C	441.48	-26.11	17.84	0.07	-	-	-	-	-	-

Appendix F

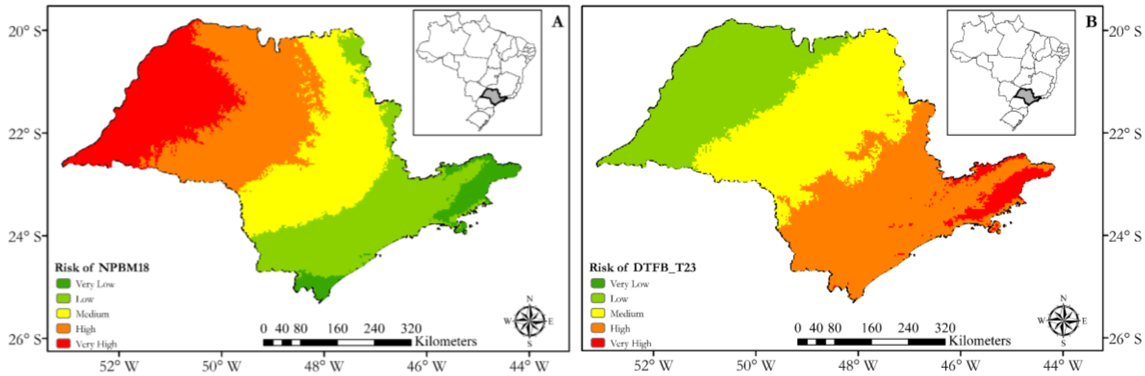

Figure F1. The annual risk of HLB occurrence in São Paulo, Brazil, based on based on number of psyllid occurrence and Number of generations (NPBM18) (A), combination with number of days with average temperature below 23 °C (DTFB_T23) (B).

Appendix G

Table G1. Coefficients used to spatialize the relative eradication for the: n number of psyllid combinated with number of psyllid generation (NPG) based in degree-days and number day with temperature below that 23 °C for the monthly period for the state of São Paulo, Brazil.

Models	Months	a	b	c	d	e	f	g	h	i	j
N° psyllid+NPG	Jan	-64574.4	-6891.1	310.2	-14.96	-148.8	5.7	0.0005	-10.9	-0.02	-0.29
	Feb	16690.0	-1366.2	924.6	-13.90	-62.0	5.3	0.001	17.7	-0.32	-0.11
	Mar	161114.6	604.3	5221.4	-49.66	-181.8	18.1	0.002	148.6	-1.12	-0.41
	Apr	-270933.6	-12607.7	-6204.4	-44.49	-315.5	-64.5	0.002	4.6	-0.81	-0.47
	May	-988795.5	-32793.7	-25435.5	-10.43	-385.4	-177.5	0.001	-332.2	-0.80	0.22
	Jun	-326992.6	-16412.8	-5038.2	5.33	-214.1	-12.9	0.0001	-132.4	-0.08	0.17
	Jul	26400.5	-2689.2	2630.0	7.74	-112.9	20.6	0.0001	47.4	-0.13	0.25
	Agu	-223336.5	-12551.8	-3414.8	0.69	-178.4	-10.2	0.0002	-98.6	0.07	0.001
	Sep	-224765.4	-9011.3	-4882.4	3.06	-187.4	-40.5	0.0001	-20.0	-0.36	0.25
	Oct	-297734.9	-9550.8	-7800.6	5.36	-133.0	-57.4	0.00004	-83.3	-0.23	0.24
	Nov	-127082.1	-2127.8	-4321.9	1.70	-26.1	-35.4	0.0001	-29.7	-0.25	0.17
	Dec	-138009.5	-4173.7	-3788.4	1.84	-60.8	-28.4	0.0001	-37.4	-0.19	0.14
N° dias Temp< 23 °C	Jan	60.7	-0.99	1.65	0.007	-	-	-	-	-	-
	Feb	34.2	-0.85	1.08	0.008	-	-	-	-	-	-
	Mar	49.9	-1.82	1.77	0.007	-	-	-	-	-	-
	Apr	56.9	-2.57	2.09	0.004	-	-	-	-	-	-
	May	49.0	-1.82	1.30	0.0002	-	-	-	-	-	-
	Jun	43.3	-1.18	0.86	-0.0003	-	-	-	-	-	-
	Jul	43.3	-1.65	1.07	-0.0001	-	-	-	-	-	-
	Agu	52.0	-2.91	1.92	0.001	-	-	-	-	-	-
	Sep	3.2	-3.75	1.43	0.004	-	-	-	-	-	-
	Oct	4.8	-4.13	1.75	0.005	-	-	-	-	-	-
	Nov	34.3	-2.85	1.85	0.006	-	-	-	-	-	-
	Dec	58.3	-1.71	1.89	0.007	-	-	-	-	-	-

Appendix H

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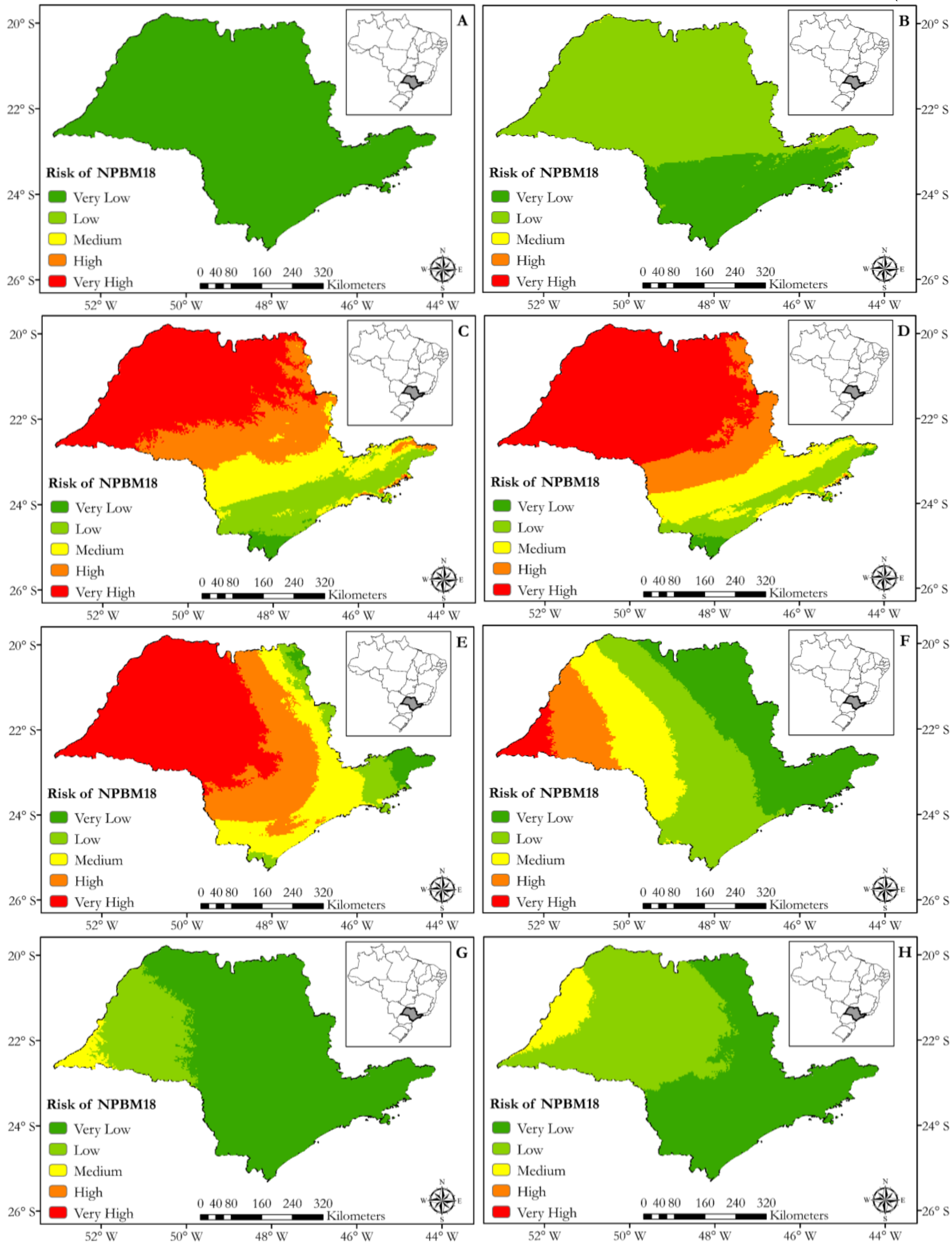
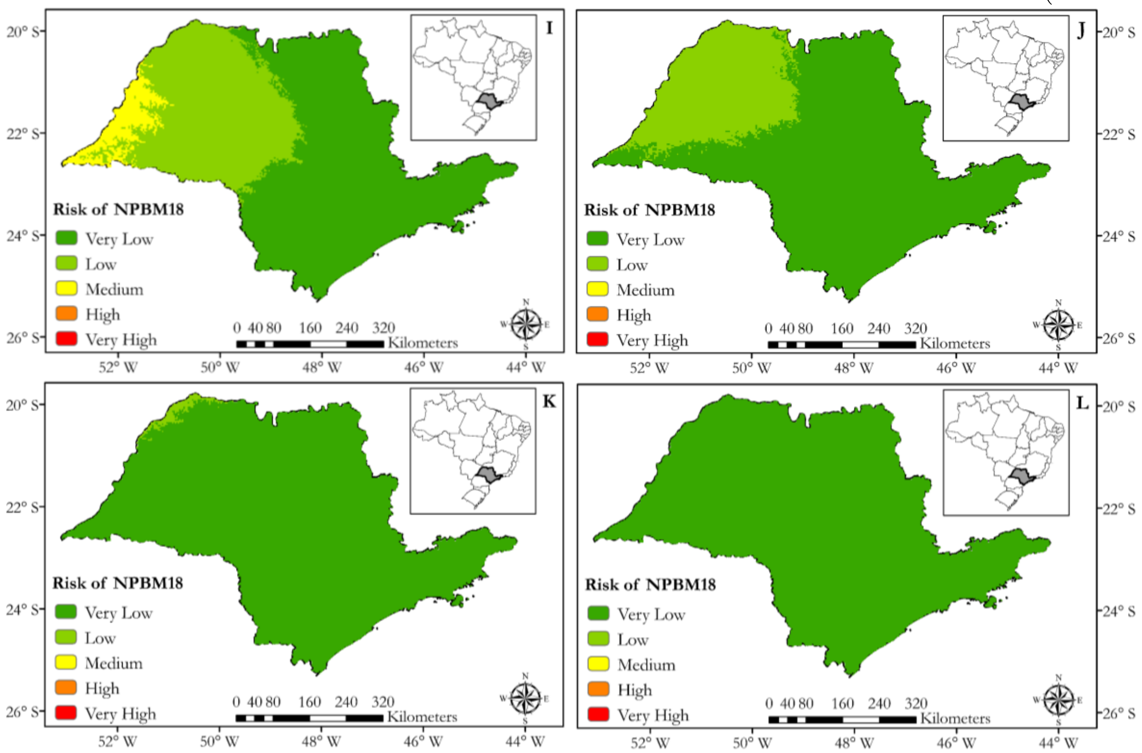


Figure H1. Average monthly Asian psyllid occurrence risk in the state of São Paulo, Brazil, based on the combination of the number of psyllid and the number of psyllid generations (NPG), determined by degree-days, in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)



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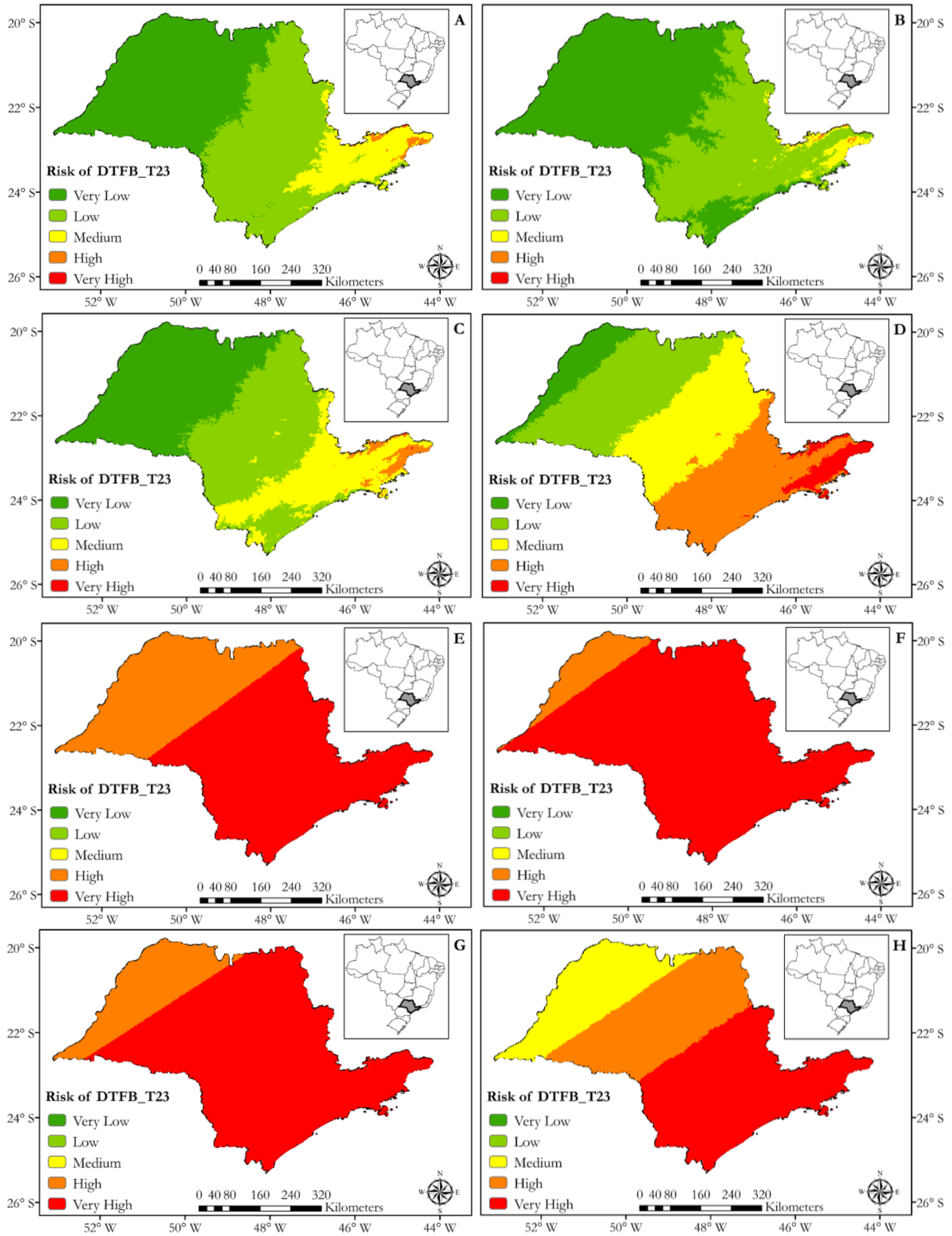

Figure H2. Average monthly Asian psyllid occurrence risk in the state of São Paulo, Brazil, based on days with average temperature below 23 °C in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).

(Conclusion)

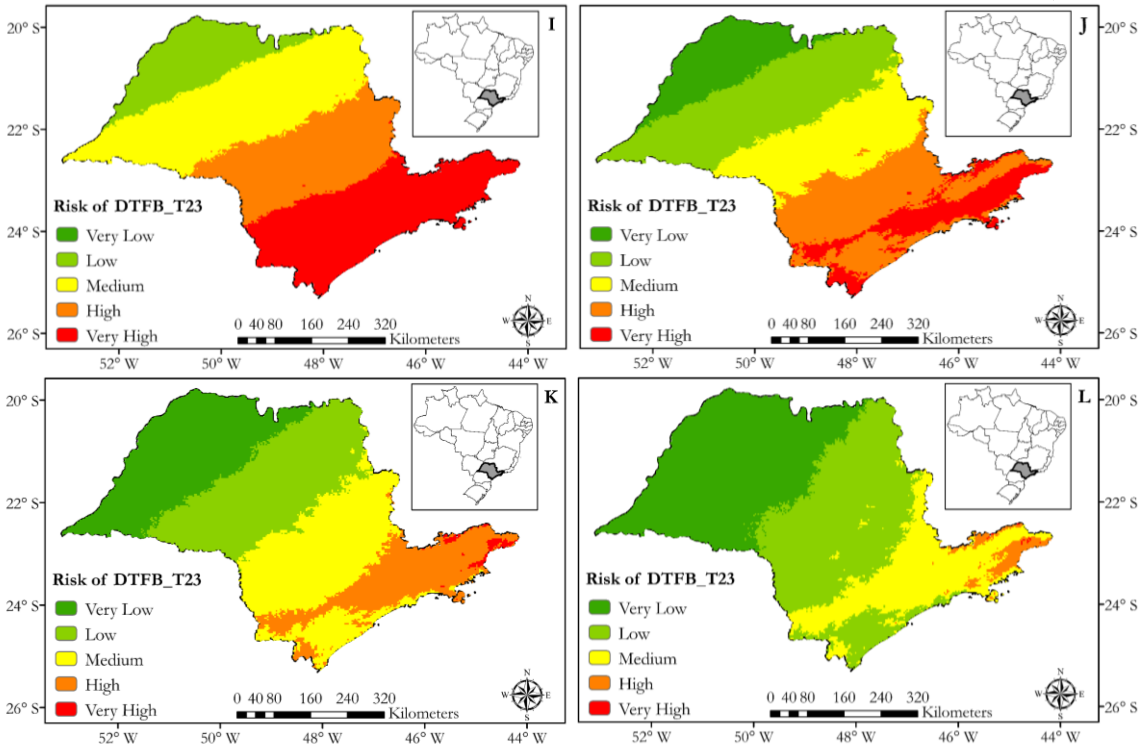

Figure H2. Average monthly Asian psyllid occurrence risk in the state of São Paulo, Brazil, based on days with average temperature below 23 °C in the months of January (A), February (B), March (C), April (D), May (E), June (F), July (G), August (H), September (I), October (J), November (K) and December (L).