

Climate-based seasonal dynamics of the invasive red palm mite *Raoiella indica*

Ricardo Siqueira da Silva,^{a*}  Elisângela Gomes Fidelis,^{b,c} George Amaro,^d Rodrigo Soares Ramos,^b  Paulo Antônio Santana Junior^b  and Marcelo Coutinho Picanço^b

Abstract

BACKGROUND: *Raoiella indica* Hirst (Acari: Tenuipalpidae) is the most critical coconut and banana pest recently introduced in Brazil. Once the mite pests are introduced, it is essential to understand their dynamics in important crops under open-field climatic conditions to implement strategies for their management and determine the periods when species populations may increase in the field. Modelling tools have been used to determine the potential distribution of species and implications for the management of invasive species. Thus, our aim in this study was to determine the seasonal variation in *R. indica* and the influence of the monthly climate using CLIMEX modelling. We adjusted the CLIMEX model for *R. indica* based on distribution data, additional biological characteristics, and fluctuations in the *R. indica* population in a commercial coconut plantation.

RESULTS: The model for the current climate shows a good match between the ecoclimatic index and the global distribution of *R. indica*. The model results demonstrate that most states of Brazil and several regions worldwide include areas with highly suitable climatic conditions for *R. indica*. We observed variations in the density of *R. indica* in commercial coconut crops, with the highest incidence occurring during the first months of the year.

CONCLUSION: Our results showed different alterations in seasonal suitability for *R. indica* that may provide information for the implementation of methods for time management, such as strategies for sampling and control during periods with a high degree of suitability for *R. indica*.

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Keywords: invasive species; red palm mite; coconut; banana

1 INTRODUCTION

In agriculture, pest invasions are among the reasons for decreases in productivity and economic losses.^{1–3} Losses of more than US\$ 336 billion per year are caused by species invasions worldwide, which corresponds to millions of tons of food, fibre, and biofuels annually.⁴ Thus, it is fundamental to have an in-depth knowledge of the factors involved in invasive species population dynamics to determine areas with suitable climate conditions for these species in both space and time.

Modelling tools have been used to determine the potential distribution of species,^{5–9} and MaxEnt and CLIMEX have been the most commonly used algorithms for this purpose.^{5,10} CLIMEX software is considered a comprehensive and reliable modelling tool that is mainly used to produce niche models based on parameters that have an ecophysiological basis.

MaxEnt is a correlative method for making predictions from presence data; however, it does not produce spatial–temporal dynamic models.^{5–9} However, CLIMEX considers spatial–temporal dynamics in climate suitability for ectothermic species. This tool provides map sequences displaying the changes in suitability in both space and time,¹⁰ which enables the creation of sequences of maps that can be used to visualize the spatio-temporal dynamics of climate suitability by means of the weekly growth index (GI_w). In favourable seasons, the GI_w is maximized, and in unfavourable seasons, the GI_w

is minimized. Therefore, it is possible to identify changes in suitability through a map sequence.¹⁰ These maps provide useful information to verify the suitable periods for species in space and time.^{11–13}

The biological and ecological processes associated with most species are determined by climatic conditions.^{14,15} Modelling and assessing the seasonal variations in species in a field crop are essential tools when designing strategies and policies to address invasive species present in agricultural systems. There have been several modelling studies involving pests such as insects, pathogens, and weeds.^{8,13,16} Despite the recent attention devoted to insect, pathogen and weed invasions, there is still a lack of sufficient research on the modelling and assessment of the dynamics of mite species.

* Correspondence to: RS Silva, Departamento de Agronomia, Universidade Federal dos Vales do Jequitinhonha e Mucuri, Diamantina, MG 39100-000, Brazil. E-mail: ricardo.ufvjm@gmail.com

a Departamento de Agronomia, Universidade Federal dos Vales do Jequitinhonha e Mucuri, Diamantina, Brazil

b Departamento de Entomologia, Universidade Federal de Viçosa, Viçosa, Brazil

c Pesquisa, Embrapa Cerrados, Brasília, Brazil

d Pesquisa, Embrapa Roraima, Boa Vista, Brazil

Mites are a diverse taxon; their status as agricultural pests has increased since the 1950s, and they have recently become a threat due to invasion. These invasions have been associated with foreign trade and anthropogenic spreading pathways related to tourism and immigration from bordering countries, which may introduce exotic plants with invasive species.^{17,18} Once mite pests are established, it is crucial to understand their dynamics in crops under open-field climatic conditions to implement management strategies and determine the climate factors that may reduce or increase species' populations in the field. An example of a recently introduced pest in the American continent is the red palm mite *Raoiella indica* Hirst (Acari: Tenuipalpidae).¹⁹

Raoiella indica is the most critical coconut and banana pest recently introduced in the Americas.^{19–23} This mite causes yellowing and necrosis of leaves and consequently losses of fruit production.^{20,24,25} In the Americas, *R. indica* has also expanded its host range, attacking several species of exotic or native palms (Arecaceae), Heliconiaceae, Cycadaceae, Musaceae, Pandanaceae, Strelitziaceae and Zingiberaceae, threatening natural environments and ornamental plants.^{20,26–28} *Raoiella indica* was first reported in the Caribbean in 2004,²⁹ spreading since then to several countries in the American continent and the Caribbean.^{19,26,30–32} In Brazil, this species was first reported in the northern region in 2009²⁷ and has dispersed to all Brazilian regions, including north-eastern regions,²¹ where 81% of the coconut production is concentrated, which represents an economically important resource.³³ Brazil is the third and fourth largest producer of coconut and banana, respectively.³⁴ Because coconut and banana are a significant source of livelihood in many regions of the world, attacks of *R. indica* in new areas may increase the risk of unemployment if not properly managed.

Most of the results of niche models, such as CLIMEX, are presented with only a map of the potential distribution of the species. Thus, variation in the suitability during each month should be investigated to better understand the temporal dynamics of favourable conditions for this species. Our aim in this study was to determine the seasonal variations in *R. indica* and the influence of the monthly climate using CLIMEX modelling.

2 MATERIALS AND METHODS

The experiments were divided into three sections. Initially, pest population dynamics were monitored in the open field. Then, a

model was built to identify areas suitable for *R. indica*. Finally, the model was verified by comparing the field observations with the model projections.

2.1 Field monitoring

The study of the *R. indica* population dynamics was conducted from January to December in a commercial coconut plantation of the 'Green Tall' variety in the municipality of Boa Vista, Roraima, Brazil (02° 50' 36.2" N, 60° 44' 12.0" W). The plantation was approximately 0.5 ha in size, with dimensions of 5.0 × 6.0 m, and the coconut plants were 8 years old. Each month, 20 plants were sampled randomly, and five leaflets were taken from the central region of one leaf was taken from the basal region of the plant (14th – 16th). The leaflets were individually placed in plastic bags and transported in a Styrofoam box to the Entomology laboratory at Embrapa Roraima. The mobile stages (larva, protonymph, deutonymph, and adult) of *R. indica* and its eggs laid on the leaflets were counted under a stereomicroscope (40x). Climate data related to temperature and precipitation were recorded at a weather station installed at the study site during the trial.

2.2 Model building

2.2.1 Distribution of *Raoiella indica*

Records of *R. indica* were collected from field surveys and the published literature.^{21,27,35,36} The records of *R. indica* were concentrated in countries in Asia, Africa, America, and the Middle East. A total of 255 records of *R. indica* occurrences are shown in Fig. 1.

2.2.2 CLIMEX

As a semi-mechanistic modelling package, CLIMEX is especially well suited for estimating the potential distributions of poikilothermic species such as mites.¹⁰ Using climatic parameters derived from biological information on the species and known distribution data, CLIMEX makes projections of a species' potential distributions.¹⁰ Version 4.0 of the software also enables the user to create sequences of maps visualizing the spatial-temporal dynamics of climate suitability using the GI_w , in which a scale from zero to one is applied to describe suitable conditions for the growth of a population.¹⁰ In suitable seasons, the GI_w is maximized, whereas it is minimized in unsuitable seasons.

The growth and stress indices are combined into an average yearly ecoclimatic index (EI); the EI provides an overall measure of the climatic suitability of a location for a target species. EI values

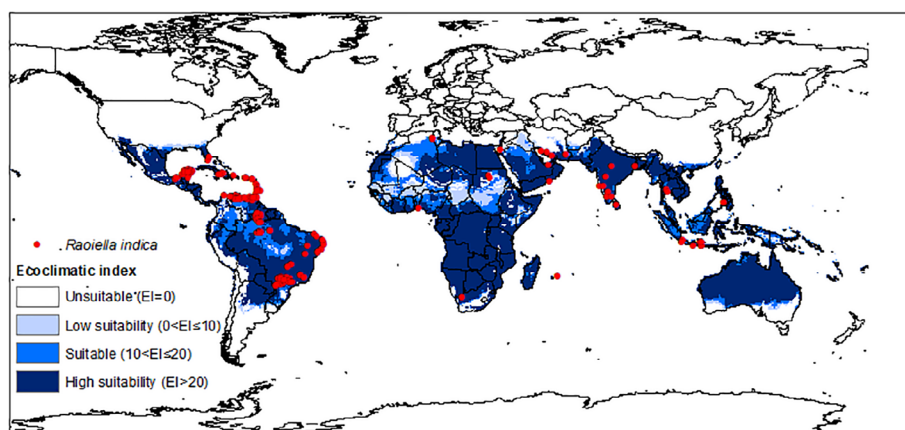


Figure 1 Known distribution of *Raoiella indica* in the world and the ecoclimatic index (EI) for *Raoiella indica*, modelled using CLIMEX for the current time period. [Color figure can be viewed at wileyonlinelibrary.com]

are scaled from 0 to 100.¹⁰ Thus, EI values equal to 0 were classified unsuitable; 0–10, low suitability; 10–20, suitable; and equal to or higher than 20, high suitability.³⁷ The model fit well based on the actual occurrence records of *R. indica*.

2.2.3 Calibration parameters in CLIMEX software and model validation

We adjusted the CLIMEX model for *R. indica* based on biological data on the thermal requirements of *R. indica* and fluctuations in *R. indica* populations in a commercial coconut plantation and regions in Asia, Africa, and the Middle East where *R. indica* occurs. Then, data from Central and South American records were used for model validation. In this step, the CliMond 10' gridded climate data were used.³⁸ The average minimum monthly temperature (T_{\min}), average maximum monthly temperature (T_{\max}), averaged monthly total precipitation (P_{total}) and relative humidity at 09:00 h (9 a.m. RH) and 15:00 h (3 p.m. RH) were used to represent the historical climate (data from 1961 to 1990, 30 years centred on 1975). The values were adjusted accordingly to match the predictions of CLIMEX and the distribution of *R. indica*. We verified whether the occurrence records for Central and South America fell within the high suitability categories to confirm that the values selected for the various parameters in CLIMEX were suitable.

2.2.4 Temperature index

Fidelis *et al.*³⁹ studied the thermal requirements of *R. indica*, with results indicating that at 14.79 °C is the low threshold temperature, and above 34 °C, the mites survive until only the larval stage. Thus, we used a low limiting temperature (DV0) of 14.79 °C and a high limiting temperature (DV3) of 34 °C. Temperatures of 20 to 30 °C are favourable for *R. indica* according to the observed patterns of the density of *R. indica* within the monitored areas in Brazil; thus, we set the lower (DV1) and upper (DV2) optimal temperatures to 20 °C and 30 °C, respectively. *Raoiella indica* requires 208.33 °C days for full development. Thus, the degree days parameter (PDD) was set to this value.³⁹

2.2.5 Moisture index

According to the distribution of *R. indica*, we used parameters representative of different geographical distributions provided by CLIMEX. The lower moisture threshold (SM0) was set at 0; the lower optimum soil moisture threshold (SM1) and the optimum upper threshold (SM2) were 0.001 and 0.2, respectively. These values provided an excellent fit to the observed distribution of *R. indica* in desert regions. The upper soil moisture threshold (SM3) was set at 2 because this species is present in wet tropical regions. These settings allowed better adjustment according to the location records of *R. indica* and the observed patterns of the density of *R. indica* within the monitored areas.

2.2.6 Stress indices

2.2.6.1. Cold stress. The degree-day cold stress mechanism was used. A species may not survive if exposed to excessively low temperatures. Thus, the cold stress degree-day threshold (DTCS) was set at 15 °C days. This value was chosen according to the desert template proposed by CLIMEX. The cold stress degree-day rate (DHCS) was set at -0.0005 wk^{-1} . These values were chosen in terms of the prediction based on the known distribution of *R. indica* in regions of South Africa (Namibia), Northern Africa (Sudan), North Africa (Tunisia) and the Middle East (Iran, Israel, Oman and the United Arab Emirates).

2.2.6.2. Heat stress. The temperature threshold for heat stress was set higher than the developmental threshold (34 °C)³⁹ to allow persistence within the known *R. indica* distribution in hot desert climate regions. We therefore set the heat stress parameter (TTHS) at 39 °C and its accumulation rate (THHS) at 0.001 wk^{-1} . The values listed allowed better adjustment according to the occurrence of *R. indica* in hot desert climate regions.

2.2.6.3. Wet stress. Dislodgement of eggs and drowning of larvae by rainfall are significant causes of mortality in arthropods. In rainfall periods, a low density of *R. indica* is observed in the field, and we therefore set our wet stress parameter (SMWS) at 2, with the accumulation rate (HWS) at 0.01 wk^{-1} . These selections allowed better adjustment according to the occurrence of *R. indica*. All CLIMEX parameters are summarized in Table 1.

2.2.7 Climate data

Climate data were used to show the spatio-temporal dynamics of climate suitability for *R. indica* from January to December in a commercial coconut plantation in the municipality of Boa Vista, Roraima, Brazil. In the compare locations/year tool in CLIMEX, it is necessary to use a monthly time series of climate data. Thus, we used the high-resolution gridded data of CRU TS3.23: Climatic Research Unit (CRU) Time-Series (TS) Version 3.23 on monthly variations in climate. All the CRU TS 3.23 data are reformatted for the variables required by CLIMEX, such as precipitation, monthly average daily maximum and minimum temperature, and vapour pressure, for the period from January 1901 to December 2014. All CRU TS output files are actual values.⁴⁰ We then ran our CLIMEX model for the period of January 2012 to December 2012, representing the same period for monitoring data that were obtained for *R. indica* on coconut crops.

2.3 Model verification

Model verification was carried out by comparing the seasonal dynamics of *R. indica* in the monitored area with the weekly growth index from the CLIMEX model and local climate data.

Table 1 CLIMEX parameter values used for *Raoiella indica* modelling

Index	Parameter	Values
Temperature	DV0 = lower threshold	14.79 °C
	DV1 = lower optimum temperature	20 °C
	DV2 = upper optimum temperature	30 °C
	DV3 = upper threshold	34 °C
Moisture	SM0 = lower soil moisture threshold	0
	SM1 = lower optimum soil moisture	0.001
	SM2 = upper optimum soil moisture	0.2
	SM3 = upper soil moisture threshold	2
Cold stress	DTCS = cold stress degree-day threshold	15
	DHCS = cold stress degree-day rate	-0.0005
Heat stress	TTHS = temperature threshold	39 °C
	THHS = stress accumulation rate	$0.001/\text{week}$
Wet stress	SMWS = soil moisture threshold	2
	HWS = stress accumulation rate	$0.01/\text{week}$
Degree days	PDD = degree days threshold	208.33 °C days

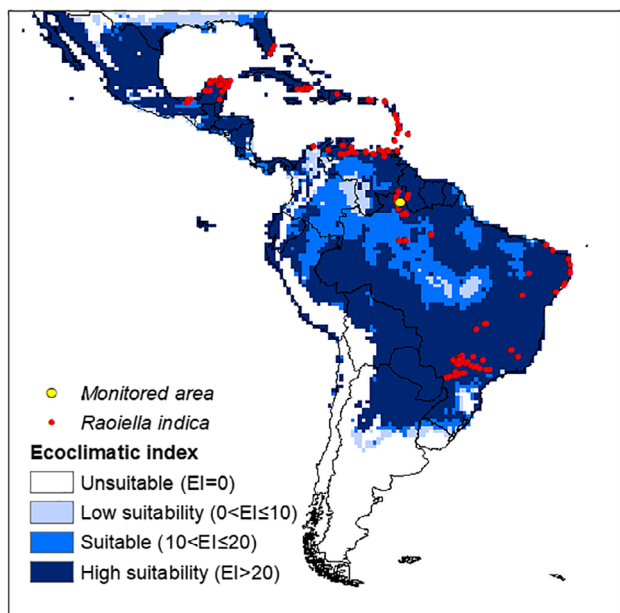


Figure 2 The ecoclimatic index (EI) for *Raiella indica* modelled using CLIMEX for the current climate in South America; the monitoring area for assessing the seasonal dynamics of *R. indica* in Boa Vista, Roraima state, is highlighted in yellow. [Color figure can be viewed at wileyonlinelibrary.com]

Pearson correlation analysis was performed to compare the relationship between the number of *R. indica* and the GI_w for the monitored area (SigmaPlot v12.5, Systat Software Inc, San Jose, CA, USA).

3 RESULTS

The CLIMEX model for the current climate showed a good match between the EI and the known global distribution of *R. indica*

(Fig. 1), indicating that the values adjusted for the parameters in CLIMEX were valid. This model showed large areas highly suitable for *R. indica* in Central and South America, Sub-Saharan and Africa, Asia, and Oceania (Fig. 1).

In South America, most states of Brazil include areas with highly suitable climatic conditions for *R. indica*, except the central region of Santa Catarina and northern Rio Grande do Sul (Fig. 2). Argentina, Bolivia, Ecuador, French Guiana, Guyana, Peru, Paraguay, Suriname and Venezuela also include large areas that are highly suitable for *R. indica* (Fig. 2).

On the African continent, well-known coconut and banana producers such as Angola, Cameroon, Equatorial Guinea, the Democratic Republic of the Congo, Mozambique, Tanzania, and Uganda also include large areas that are suitable or highly suitable for this pest (Fig. 1). The areas in Algeria, Mali, Mauritania, South Africa, Europe, and large areas in the Middle East and South Australia are mainly unsuitable for *R. indica* (Fig. 1).

In Pacific Asia, Indonesia and the Philippines are the largest producers of coconut and banana and present suitable areas for *R. indica*.

The monitored area in Roraima presents highly suitable climatic conditions; the highest densities of *R. indica* were observed between January and April and the lowest were observed between May and September (Fig. 3). The projected GI_w was in accordance with the field monitoring data (Fig. 4). A significant positive correlation was found between the number of *R. indica* and the GI_w according to the Pearson correlation coefficient ($r = 0.71, n = 12, P < 0.01$). During January–December, the model showed a GI_w above 0, with the highest GI_w during February corresponding well with the highest observations of *R. indica*. A decrease in the GI_w between March and November matched well with the low density of *R. indica* (Fig. 3). In most of the months, the observed *R. indica* fluctuations corresponded well with the GI_w . Exceptions were during December, when the pattern of the growth indices increased, and *R. indica* was lower than in October and November (Fig. 3).

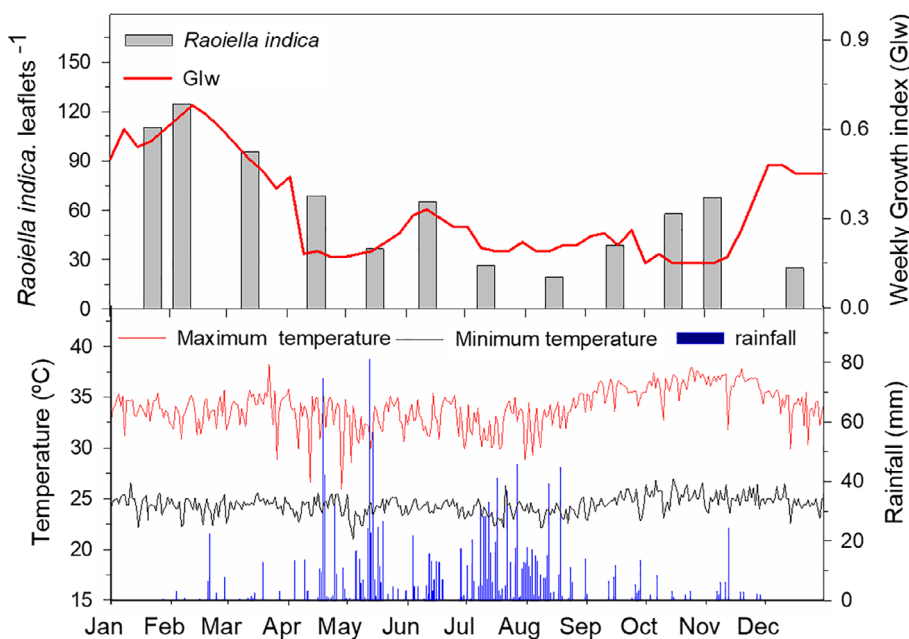


Figure 3 Seasonal dynamics of *Raiella indica*, CLIMEX weekly growth index (GI_w), temperature and rainfall in Boa Vista, Roraima, Brazil, from January to December 2012. [Color figure can be viewed at wileyonlinelibrary.com]

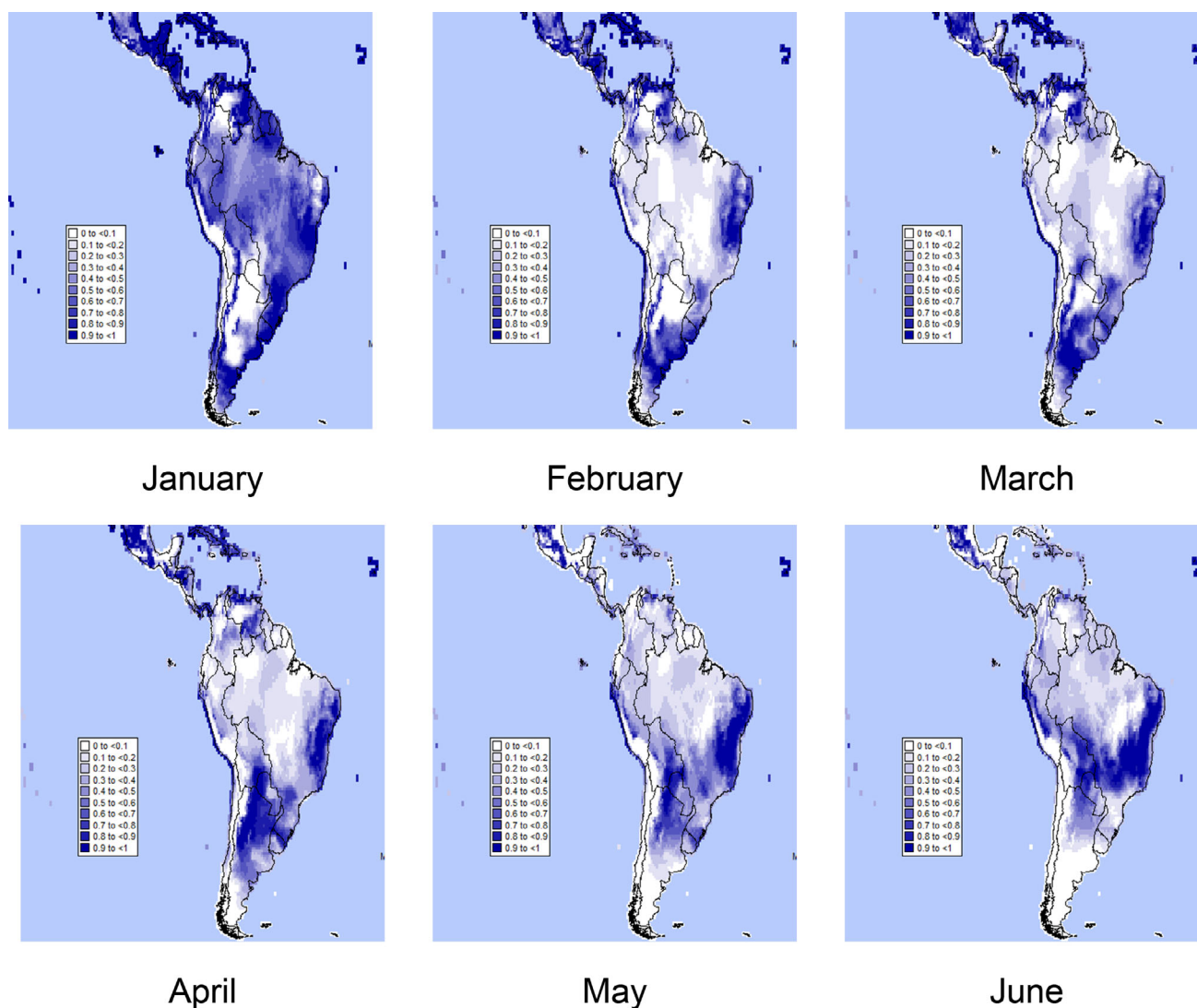


Figure 4 Monthly variability in climatic suitability for *Raoiella indica* in South America based on the growth index (0 to 1). [Color figure can be viewed at wiley onlinelibrary.com]

The observed population reduction also coincided with the high intensity of precipitation in May and the period from July to September (Fig. 3). The highest temperature was observed in the periods of lowest rainfall, which were from January to April and October to December, when the densities of *R. indica* were high (Fig. 3).

We observed that climate suitability for *R. indica* during the year presented spatial–temporal variations (Fig. 4). In January, most areas in South America showed highly suitable climatic conditions for *R. indica* (Fig. 4). From February to April, the climatic suitability decreased progressively, limiting the suitable areas to northern, southern, and central eastern Brazil and areas in Bolivia and northern Paraguay (Fig. 4). From July to September, the climatic suitability is restricted to the east coast of Brazil and southern Paraguay. From August to December, the climatic suitability improves again in most areas (Fig. 4).

4 DISCUSSION

The CLIMEX model proposed in this study is more suitable than the potential distribution model for *R. indica* based on the maximum entropy model³⁵ due to the favourable use of approximate

biological data regarding temperature and RH.⁴¹ These models projected areas that were relatively restrictive for the species since its biological parameters were not well known. In contrast to the two cited models, the CLIMEX model developed in this study projected areas with highly suitable climatic conditions for *R. indica* in most regions of Brazil, except for some parts of southern Brazil (Figs 1 and 2). Parameters and values were chosen based on the objective of constructing a CLIMEX model that could determine the climate favourable for *R. indica*. The parameter settings were performed according to the biological life table study performed by Fidelis *et al.*,³⁹ occurrence in monitored areas in Brazil and known distribution of *R. indica* in Asia, Africa, and the Middle East. In our modelling exercise, attempts were made to ensure a 99% match between the model predictions and the known distribution of *R. indica* in Central and South America.

The final model corresponded well with the observed distribution of *R. indica* and very well with its worldwide distribution. The recent dispersion of *R. indica* to southern Brazilian regions^{21,42–44} confirms that this species can become established in areas with mild temperatures but not in areas with low temperatures, as projected by our model and confirmed by surveys by Barroso *et al.*⁴⁴ These authors did not find *R. indica* in

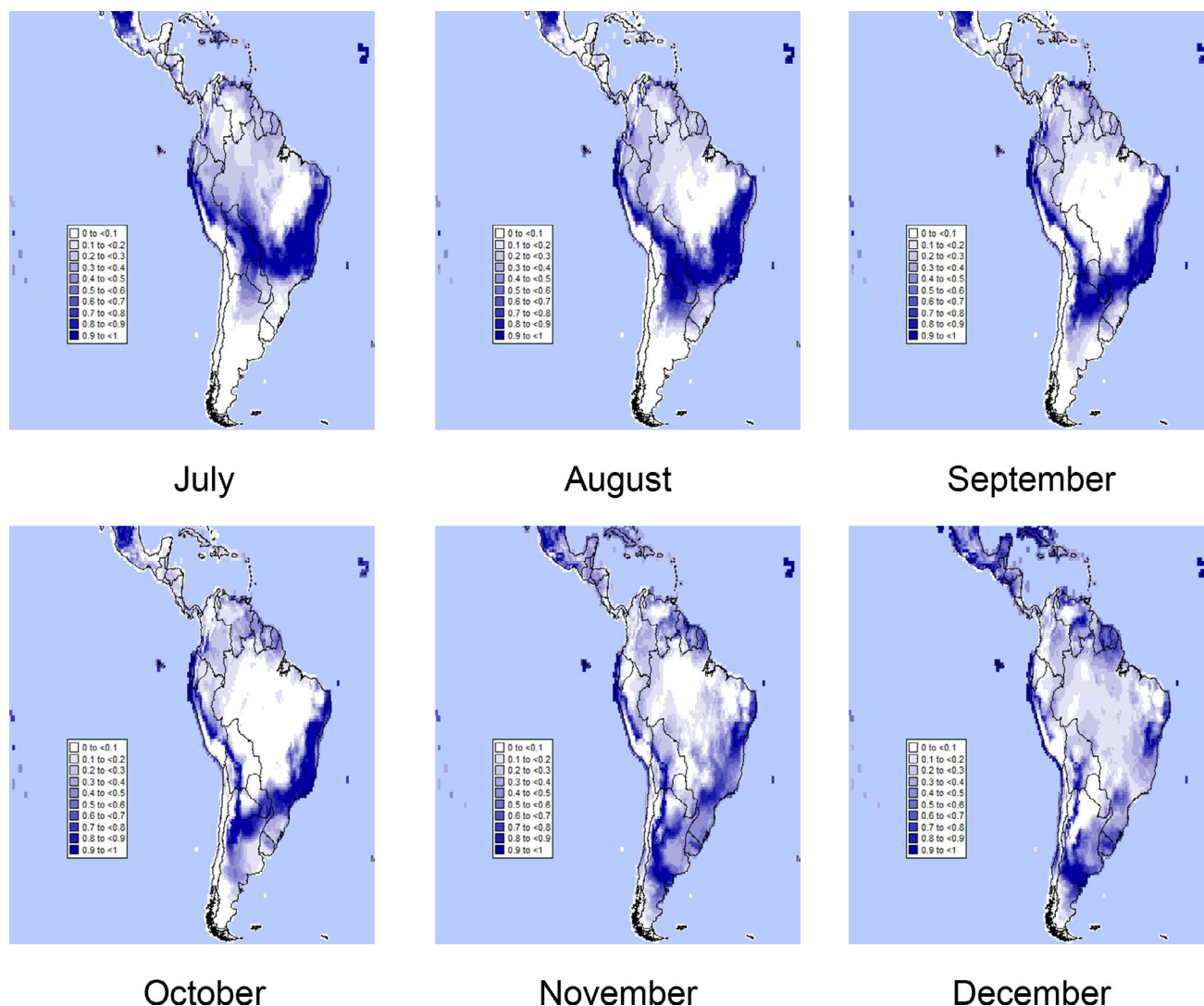


Figure 4 (Continued)

municipalities of the south region of Brazil where the average minimum monthly temperatures are less than 9 °C.

Furthermore, the results of this study highlight some potentially threatened countries at risk of *R. indica* invasion, since many coconut- and banana-producing areas are highly suitable according to the model proposed here. Dispersal of *R. indica* for those areas can occur by transportation of infested plants, principally ornamentals and coconut plantlets or other host plants.²⁷ Among the top 20 countries in which coconut is economically and socially important,³⁴ nine (e.g. Papua New Guinea, Vietnam, Mozambique, Vanuatu, Ghana, Kenya, Fiji, Solomon Islands, and Myanmar) present highly suitable climatic conditions for *R. indica*³⁶ and are free from this pest (Fig. 1). For banana, following the same criteria, the main countries threatened by *R. indica* are Ecuador, Angola, Uganda, Vietnam, the Democratic Republic of the Congo, Papua New Guinea, Cameroon, and Mozambique.

The model results showed that the climate suitability for *R. indica* varies in the identified areas during the months of the year (Fig. 4). Thus, the amplitude of climatic factors influences the seasonality of *R. indica*. In Brazil, the highest densities of *R. indica* were observed from January to March, which corresponds mostly to

summer, while the lowest densities of *R. indica* were observed from April to December (i.e. autumn, winter and spring). Temperature varies significantly during the seasons in Brazil, ranging from 40 °C to 0 °C depending on the region (WorldClim – <http://www.worldclim.org>). Therefore, the seasonal variation in temperature might be one of the main factors affecting the population dynamics of *R. indica*.

The fluctuations in the *R. indica* population and the period of rainfall (Fig. 3) indicate the influence of this climatic factor on the seasonality of *R. indica*. In the CLIMEX model, rainfall is indirectly considered a wet stress parameter. However, rainfall can also cause mortality of *R. indica* by removing individuals from plants, especially nymphs and eggs.^{20,45,46} Thus, we highlight the importance of rainfall as an agent of natural *R. indica* mortality. This observation implies that the application of artificial irrigation in periods with the lowest incidence of rainfall and suitable climate conditions for population growth of *R. indica* may be an alternative to reduce the *R. indica* population. Our findings may be a starting point for future studies of artificial irrigation in coconut and banana plantations in terms of economic viability.

The model of seasonal dynamics based on the growth index can be used by coconut and banana farmers for monitoring and making decisions about the control of *R. indica*. The seasonal variation model for *R. indica* may provide useful complementary information that could be used in planning strategies to minimize economic impacts in favourable seasons with a high abundance of *R. indica*.

In addition to climate, other factors can affect species distributions and seasonal dynamics, including host plant distributions, the presence of natural enemies and other non-climatic factors.⁴⁷ It is essential to note that this model did not consider these factors, and our research could serve as a starting point for future studies. Recently, studies have shown the effects of different temperature exposure regimens on the life history of insects.^{48–51} These findings may be used to refine and accelerate the adjustment of parameters in modelling by considering the effects of fluctuating temperatures on biological parameter species. Thus, uncertainties need to be considered, and further studies on *R. indica* with fluctuating temperatures may be a starting point to improve the present model.

Based on this study, attention should be given to developing *R. indica*-resistant or tolerant varieties of coconut and banana, especially for areas suitable for the growth of *R. indica* populations and regions with low precipitation, such as the northeast coast of Brazil. Thus, this model might be useful as a tool for guiding plant geneticists in their breeding programmes.

In summary, we observed variations in the density of *R. indica* in commercial coconut crops in Brazil, with the highest incidence occurring during the first months of the year. The lowest incidence of *R. indica*, especially in the central region, occurs in July–September. These seasonal variations match the applied spatial–temporal dynamic climate model and rainfall periods. This model shows different alterations in seasonal suitability for *R. indica* that may provide useful information for implementing methods for time management, such as the strategies adopted for sampling and control during periods with a high degree of suitability for *R. indica*. In addition, our results may be used to design quarantine measures to prevent the introduction and establishment of *R. indica* in new areas.

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