

## Research Paper

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### Author for correspondence:

Christian S. A. Silva-Torres,  
Email: [sherleyjbt@yahoo.com](mailto:sherleyjbt@yahoo.com)

# Potential displacement of the native *Tenuisvalvae notata* by the invasive *Cryptolaemus montrouzieri* in South America suggested by differences in climate suitability

Larissa F. Ferreira<sup>1</sup> , Christian S. A. Silva-Torres<sup>1</sup> , Jorge B. Torres<sup>1</sup>   
and Robert C. Venette<sup>2</sup> 

<sup>1</sup>Universidade Federal Rural de Pernambuco (UFRPE), Departamento de Agronomia – Entomologia, Rua Dom Manoel de Medeiros, s/n, Dois Irmãos, 52171-900, Recife, PE, Brazil and <sup>2</sup>Northern Research Station, USDA Forest Service, 1561 Lindig Street, St. Paul, MN 55108-6125, USA

## Abstract

*Tenuisvalvae notata* (Mulsant) (Coccinellidae) is a predatory ladybird beetle native to South America. It specializes in mealybugs prey (Pseudococcidae), but relatively little is known about its ecology. In contrast, the ladybird beetle *Cryptolaemus montrouzieri* Mulsant (Coccinellidae) is indigenous to Australia and has been introduced to many countries worldwide including Brazil for biological control of mealybugs. The potential impacts of these introductions to native coccinellids have rarely been considered. The software CLIMEX estimated the climate suitability for both species as reflected in the Ecoclimatic Index (EI). Much of South America, Africa, and Australia can be considered climatically suitable for both species, but in most cases, the climate is considerably more favorable for *C. montrouzieri* than *T. notata*, especially in South America. The CLIMEX model also suggests seasonal differences in growth conditions (e.g. rainfall and temperature) that could affect the phenology of both species. These models suggest that few locations in South America would be expected to provide *T. notata* climatic refugia from *C. montrouzieri*. Although other ecological factors will also be important, such as prey availability, this analysis suggests a strong potential for displacement of a native coccinellid throughout most of its range as a consequence of the invasion by an alien competitor.

## Introduction

Classical biological control programs involve the intentional introduction of a natural enemy (i.e., pathogen, parasite, parasitoid, or predator) from an alien pest's native range to control a pest in its adventive range (De Bach, 1968), and worldwide many important pests have been controlled using this control method (De Bach and Schlinger, 1964; Caltagirone and Douth, 1989; Evans *et al.*, 2011; Kairo *et al.*, 2013 among others). One concern is that released natural enemy species will adversely affect indigenous organisms (so-called 'non-target' species) that integrate the food web in the habitat (De Bach, 1968). Assessments of efficacy and specificity are now integral components of risk assessments before natural enemies are introduced, and rigor for those assessments has increased in recent decades.

Most successful classical biological control programs with ladybird beetles (Coleoptera: Coccinellidae) involve species with specialized diets, being primarily soft scale (Hemiptera: Coccidae) feeders (Dixon, 2000) [i.e. *Rodolia cardinalis* (Mulsant) to control *Icerya purchasi* Maskell in citrus orchards in California] (De Bach and Schlinger, 1964; Caltagirone and Douth, 1989). In contrast, most attempts to use generalist-feeding ladybird beetle species have failed to control the target species (Evans *et al.*, 2011) and occasionally resulted in non-target effects from predation upon non-intended prey, increased competition, intraguild predation, and displacement of indigenous predatory species (Elliott *et al.*, 1996; Follet and Duan, 2000; Koch *et al.*, 2006; Evans *et al.*, 2011; Sloggett, 2017).

Possibly as early as 1912, releases of *Cryptolaemus montrouzieri* Mulsant (Coleoptera: Coccinellidae), the 'mealybug destroyer', began in Central and South America (reviewed in Kairo *et al.*, 2013). This lady beetle is indigenous to Australia and can feed upon at least 94 insect species in 12 families (Babu and Azam, 1987; Kairo *et al.*, 2013). It may be one of the most widely released natural enemies having first been introduced in California between 1891 and 92 by Albert Koebele to control mealybugs (Hemiptera: Pseudococcidae) in citrus. Also, it has been released in more than 40 countries in temperate and tropical regions (Maes *et al.*, 2015). In Brazil, *C. montrouzieri* was introduced to control citrus mealybugs *Planococcus citri* (Risso) (Sanches and Carvalho, 2010; Kairo *et al.*, 2013), and occurs in various regions of

Brazil, including the Southeast and Northeast regions, in the states of São Paulo, Bahia, and Pernambuco (Sanches and Carvalho, 2010; De Bortoli *et al.*, 2014; Marques *et al.*, 2015; Lopes, 2016; Sá *et al.*, 2020).

Little attention has been given to the potential for *C. montrouzieri* to displace indigenous predatory species in Brazil. This exotic species shows overlap in food niche with Brazilian native ladybirds that prey upon mealybugs (Pseudococcidae) (Marques *et al.*, 2015; Pacheco da Silva *et al.*, 2019; Sá *et al.*, 2020). For instance, *C. montrouzieri* has been reported in the semiarid region of the state of Pernambuco, such as Petrolina, where there is the occurrence of native species such as *Tenuisvalvae notata* (Mulsant) (= *Hyperaspis notata* Mulsant) (Coleoptera: Coccinellidae), and share mealybug preys such as *Phenacoccus solenopsis* Tinsley, *Ferrisia dasylyrii* Cockerell, *Ferrisia virgata* Cockerell, and *Maconellicoccus hirsutus* (Green) (Wu *et al.*, 2014; Barbosa *et al.*, 2014a; Marques *et al.*, 2015; Lopes, 2016).

The lady beetle *T. notata* is indigenous to South America (Dreyer *et al.*, 1997a), but its ecology is largely unknown. It occurs in Brazil, Bolivia, Colombia, and Paraguay. In Brazil it has been reported from the states of Amapá, Bahia, Mato Grosso do Sul, Rio de Janeiro, Rondônia, São Paulo and Pernambuco (Dreyer *et al.*, 1997a; Peronti *et al.*, 2016). Adults and larvae of this species have a high predation rate upon mealybugs (Barbosa *et al.*, 2014a). In Colombia, it has shown a preference for *Phenacoccus herreni* Cox and Williams, whereas in Brazil and Paraguay it was associated with the cassava mealybug, *Phenacoccus manihoti* Matile-Ferrero (Löhr *et al.*, 1990; Sullivan *et al.*, 1991). In the state of Pernambuco, Brazil, *T. notata* adults have been collected in association with *P. solenopsis* and *F.* on cotton, and in association with the false cochineal scale *Dactylopius opuntiae* Cockerell on prickly pear, *Opuntia ficus-indica* (L.) (Barbosa *et al.*, 2014a; Giorgi *et al.*, 2018; Torres and Giorgi, 2018). In the state of São Paulo, *T. notata* was found in association with the pink-hibiscus mealybug *Maconellicoccus hirsutus* (Green) on *Hibiscus rosasinensis* (Malvales: Malvaceae) (Peronti *et al.*, 2016). *T. notata* was introduced successfully in Africa in the 1980s to control the cassava mealybug (Herren and Neuenschaeabder, 1991; Chakurakal *et al.*, 1994).

Forecasts of the distribution of *T. notata* and *C. montrouzieri* would be a useful first step to estimate potential regional impacts after the introduction of *C. montrouzieri* in the state of Pernambuco. Species distribution models driven by climate are particularly informative for generalist-feeding insects because suitable temperature and moisture conditions are likely to dictate geographic range limits (e.g., Jalali *et al.*, 2014; Rehman and Kumar, 2018). The resulting forecasts may be useful to identify potential areas of species co-occurrence or climatic refugia, where conditions are suitable for one species but not the other. Wyckhuys *et al.* (2009) used such an approach to estimate where a candidate parasitoid for release might co-occur with non-target prey species. Differences in climatic suitability may also provide insight into the potential outcome of the competition. For instance, Barahona-Segovia *et al.* (2016) investigating the effects of temperature on the exotic coccinellids *Hippodamia variegata* (Goeze) and *H. axyridis*, and the native *Eriopis chilensis* (Germar) in Chile have shown that *H. axyridis* had better performance at lower temperatures ( $\approx 20^\circ\text{C}$ ), which could, in turn, lead to a displacement of its current distribution in that country. On the other hand, *H. variegata* and *E. chilensis* had better performances at higher temperatures ( $30^\circ\text{C}$ ), resulting in high niche overlap and potential competition of these later species.

Thus, assessments of climate suitability may be useful to determine where an introduced natural enemy might permanently establish when the introduced natural enemy might be active (i.e., climate-driven phenology), and whether displacement of indigenous predatory species is possible.

In this context, bioclimatic models of species distribution or ecological niches are tools applied in different situations (Beaumont *et al.*, 2005), such as estimation of the distribution of invasive species (Peterson, 2003), and the pest risk assessment (Nietschke *et al.*, 2007). Under field conditions, they help to predict insect development in a range of temperatures and estimate population dynamics of pest and natural enemy species (Fan *et al.*, 1992; Briere and Pracros, 1998; Kim and Lee, 2008; Moerkens *et al.*, 2011). Therefore, this study used the CLIMEX software to estimate: (i) the potential global geographic distribution of *T. notata* and *C. montrouzieri*; (ii) the phenology of these species in four localities representing four different micro regions of the state of Pernambuco, Brazil; and (iii) the possible interactions between *T. notata* and *C. montrouzieri* in a scenario of co-existence of the two species in South America under current climate conditions.

## Materials and methods

### *Climex software*

We used the ‘compare locations’ feature within CLIMEX ver. 4.0 (Hearne Software, Melbourne, Australia) to estimate climate suitability for *T. notata* and *C. montrouzieri*. CLIMEX has been applied to a wide range of plants, insects, and pathogens. Poutsma *et al.* (2008) used CLIMEX to estimate the geographic distribution of *H. axyridis*. Similarly, Ceballo *et al.* (2010) used CLIMEX to evaluate the effects of climate conditions in southeast Queensland, Australia, on the efficacy of the parasitoid *Coccidoxenoides permirtus* Girault to control the citrus mealybug (*P. citri*).

The concepts and mathematics behind CLIMEX have been reviewed extensively elsewhere (Sutherst *et al.*, 2007). Eight parameters characterize cardinal and optimal temperatures (DV0-DV3) and moistures (SM0-SM3) for population growth; another eight or more parameters describe thresholds and rates for stress accumulation from cold, heat, drought, or wetness. Parameters used in this study are described in table 1. CLIMEX then utilizes these biologically informed parameters with climatic records to calculate a series of environmental indices. The Ecoclimatic Index (EI) represents an overall measure of climatic suitability (Sutherst *et al.*, 2007) and varies from 0 to 100. An EI = 0 indicates that the climate in an area would not allow a species to persist throughout a year, though periods may occur with ephemeral populations from seasonal immigrants. Conversely, an EI = 100 indicates perfect climate suitability for the species year-round. For intermediate cases, when EI = 1–10, the climate would be considered marginal; when EI = 11–25, the climate is favorable; when EI = 26–50, the climate is very favorable; and when EI = 51–99, the climate is nearly ideal.

### *Estimate of geographic distribution using CLIMEX*

The parameters used to estimate *C. montrouzieri* response to temperature primarily were derived from previous literature. Thus, the lower threshold temperature for population growth (DV0) was set at  $14.5^\circ\text{C}$  (Gutierrez *et al.*, 2008) and is consistent with results found by Babu and Azam (1987). Jalali *et al.* (1999)

**Table 1.** CLIMEX parameters (function 'Compare Climate') used for the estimates of the global distribution of *Cryptolaemus montrouzieri* and *Tenuisvalvae notata*

Parameter	Code	<i>C. montrouzieri</i>	<i>T. notata</i>
Temperature index (°C)			
Lower threshold temperature	DV0	14.5	15.1
Minimum optimal temperature	DV1	25	27.2
Maximum optimal temperature	DV2	30	31
Upper threshold temperature	DV3	37.5	33
Soil moisture stress index – MI			
Lower threshold soil moisture	SM0	0.1	0.1
Minimum optimal soil moisture	SM1	0.3	0.3
Maximum optimal soil moisture	SM2	1.9	1.9
Upper threshold soil moisture	SM3	2	2
Cold stress index – CS			
Threshold temperature	TTCSA	9.5	9.5
Temperature accumulation rate cold stress	THCSA	–0.01058	–0.01058
Heat stress index – HS			
Threshold temperature heat stress	TTHS	37.52	37.52
Accumulation rate heat stress	THHS	0.0744	0.0744
Threshold day-degree heat stress	DTHS	0	0
Drought stress index – DS			
Threshold drought stress	SMDS	0.1	0.1
Accumulation rate drought stress	HDS	–0.001	–0.001
Wet stress index – WS			
Threshold wet stress	SMWS	2	2
Accumulation rate wet stress	HWS	0.01	0.01
Day-degree			
Accumulation above DVO	DV0- MTS	7	7
Accumulation above DVCS	DVCS -MTS	7	7
Per generation	PDD	600	600

indicated that the optimal (minimum and maximum) temperatures for the development of *C. montrouzieri* were 25°C (DV1) and 30°C (DV2), respectively. As Saljoqi *et al.* (2014) found positive population growth at 32°C, the upper temperature threshold for *C. montrouzieri* development (DV3) was 37.5°C. This value was lower than the 38.5°C cited by Gutierrez *et al.* (2008), but their projection was beyond the range of experimental data considered. The parameters used for heat stress (thresholds and accumulation rates) were derived from Solangi *et al.* (2013), and parameters for cold stress were estimated from lower lethal time observations from Maes *et al.* (2015). Moisture requirements for growth and drought and wet stress parameters (SM0-3, SMDS, HDS, SMWS and HWS) were taken from the model developed by Poutsma *et al.* (2008) for *H. axyridis* with one modification. The threshold for drought stress accumulation (SMDS) was set to 0.1, the moisture level that is the approximate permanent wilting point for plants. Piercing-sucking insects, the primary prey for *C. montrouzieri*, are generally less abundant under such conditions (Sconiers and Eubanks, 2017) and an examination of predicted vs observed distributions in Australia provided reassurance that these parameters were adequate (table 1).

Less information was available for *T. notata*. Empirical results from Dreyer *et al.* (1997b) and Ferreira (2019) indicated *T. notata* threshold temperatures were 15.1, 27.2, 31, and 33°C for DV0, DV1, DV2, and DV3, respectively. No information has been published about the effects of extreme temperatures or moisture on *T. notata*, and not enough locations with *T. notata* have been reported to estimate CLIMEX parameters reliably through integrative geographic fitting. Thus, other parameters used in the model were the same as those used for *C. montrouzieri* (table 1). After the parameter adjustment for both species in the model, population distribution graphs were constructed based on 10-arcminute climate summaries (CM10: World 1975H\_V1.1\_WO) provided with CLIMEX.

### Phenology of ladybird beetles

Determining the seasonal phenology of ladybird beetle species is important to pest management in biological control programs, and contributes to preview the potential occurrence and relative abundance of those natural enemies in the field. Seasonal changes in the Growth Index from CLIMEX provide a good indicator of

changes in the abundance and activity of a species at a specific location (Venette, 2017). Seasonal changes in the Growth Indices were estimated for *C. montrouzieri* and *T. notata* in different locations of the state of Pernambuco, Brazil: Chã Grande (Lat:  $-8.2522$ /Long:  $-35.4549$ ), Petrolina (Lat:  $-9.3948$ /Long:  $-40.4962$ ), Surubim (Lat:  $-7.8711$ /Long:  $-35.7533$ ), and Belo Jardim (Lat:  $-8.3446$ /Long:  $-36.4134$ ). Those locations represent different climate regions within the state of Pernambuco, wherein mealybugs are considered common pests attacking fruit crops (Pacheco da Silva *et al.*, 2019), and *T. notata* has been collected in some of those locations associated with different mealybug species (Barbosa *et al.*, 2014a).

### Interaction between predators

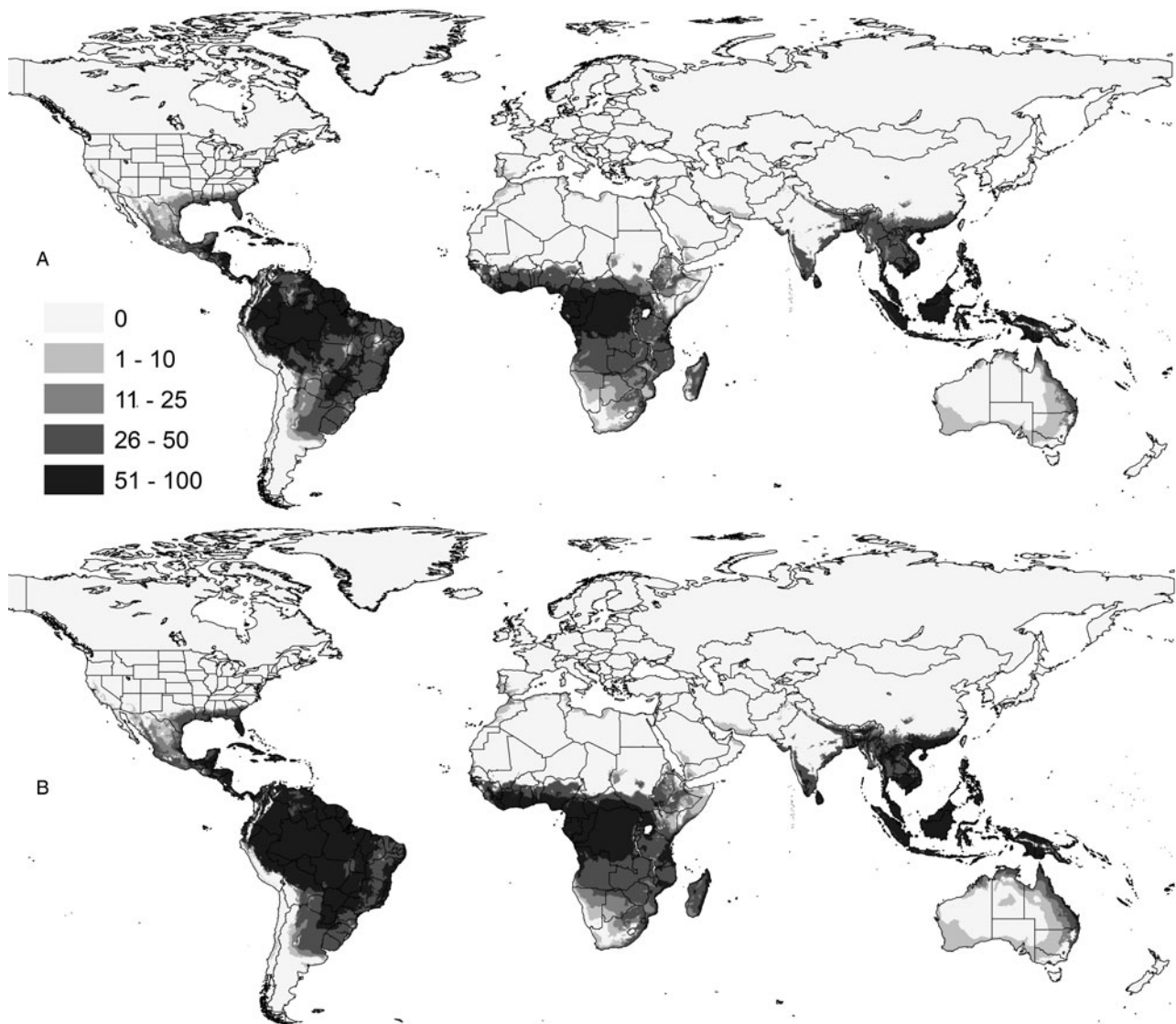
The relative favorableness of the climate for *T. notata* and *C. montrouzieri* was estimated by the difference in the EI of both species. In areas with negative values of EI, the climate is

more suitable for *T. notata*. On the other hand, in areas with positive values of EI, the climate is more suitable for *C. montrouzieri*. Finally, in areas where the difference of EI values falls between  $-3$  and  $+3$ , those locations are not likely to confer climate advantage to either of the species.

## Results

### Estimate of geographic distribution using CLIMEX

The Ecoclimatic Indices for *T. notata* and *C. montrouzieri* varied from 0–94 to 0–100, respectively. Climates that are particularly suitable for the establishment of both ladybird beetle species occur in areas of South America, Africa, and Australia. In Europe, where both species are absent, the model prediction is consistent, as well as, in North America, North of Africa and large portion of Australia, the model prediction is supported by the actual nonexistence distribution of *C. montrouzieri* and *T. notata* in those areas (fig. 1).



**Figure 1.** CLIMEX map for potential global distribution of *Tenuisvalvae notata* (a) and *Cryptolaemus montrouzieri* (b) showing the Ecoclimatic Index (EI). Darker areas are highly favorable for the occurrence of lady beetles. Unsuitable areas ( $EI = 0$ ), marginally suitable areas ( $1 \leq EI < 10$ ), suitable area ( $10 \leq EI < 25$ ), and strongly suitable areas ( $25 \leq EI < 100$ ).

Regarding *C. montrouzieri*, in general, areas near the Equator or with higher temperatures were more suitable for this species. Particularly, suitable regions occur in parts of Central America, the North region, and Northeast coast of Brazil, as well as parts of the Southeast and Midwest regions of Brazil, where the EI estimated was higher than 80, indicating a very suitable climate for *C. montrouzieri* establishment. In addition, most part of the Brazilian territory is suitable for *C. montrouzieri* with  $EI > 60$ , with only a small area with EI between 0 and 20, being those locations with low suitability for this species (fig. 2). Interestingly, in Australia where *C. montrouzieri* is indigenous, there is a less total area suitable for this species with  $EI > 80$ , since part of Australia has a prevailing desert climate, imposing difficulties to this ladybird beetle development and survival, in comparison to most part of South America, where the climate was more suitable (fig. 1).

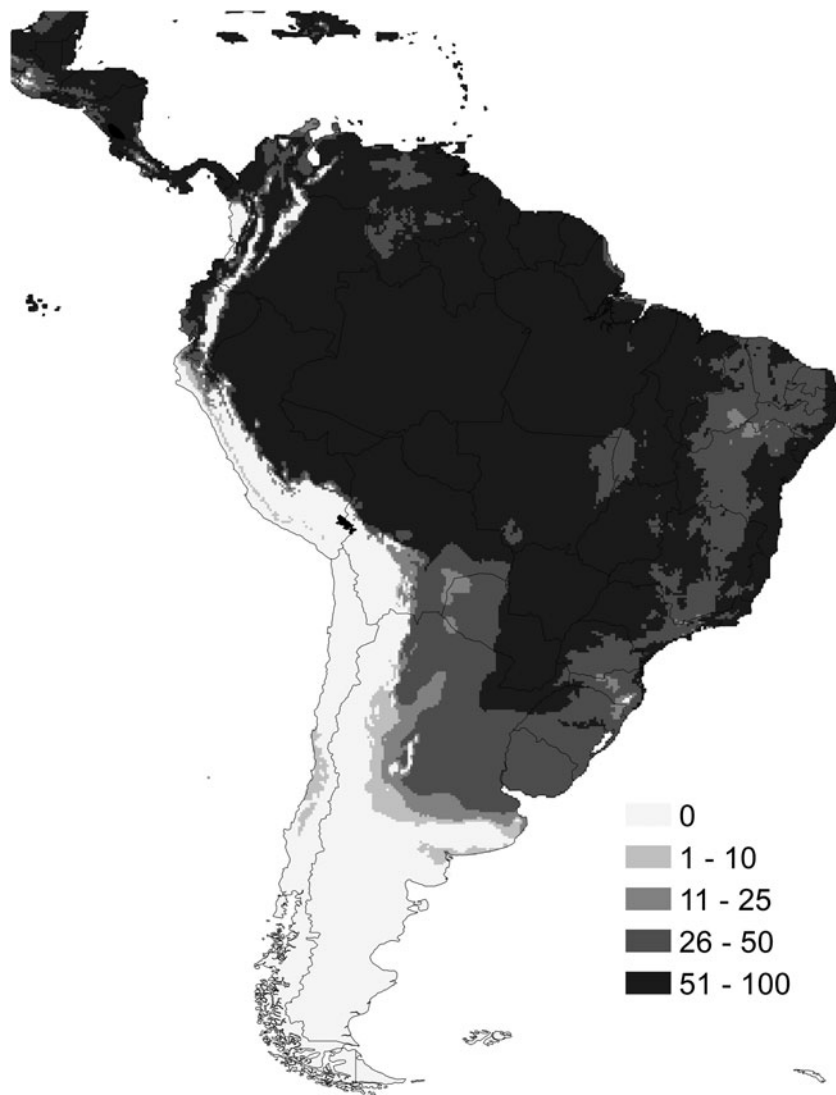
Regarding *T. notata*, the model estimated an  $EI > 80$  in parts of the North region of South America, including the North and Northeast coast of Brazil, and parts of the Brazilian Midwest on the boundaries with Paraguay (fig. 3). According to the model, the largest part of the Brazilian territory is unsuitable for *T. notata* with EI between 0 and 20, in comparison to *C. montrouzieri* (fig. 1).

### Phenology of ladybird beetles

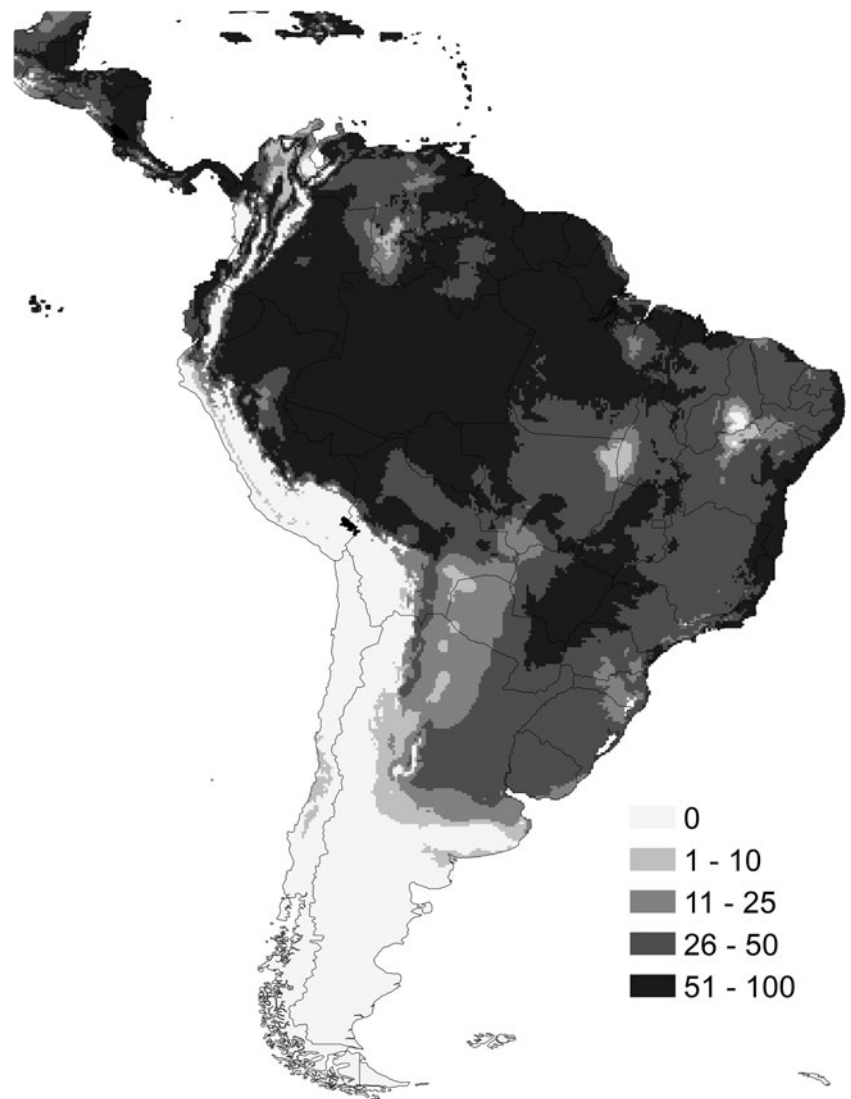
Regarding the potential phenology of *T. notata* and *C. montrouzieri* in Belo Jardim (fig. 4), Chã Grande (fig. 5), Petrolina (fig. 6) and Surubim (fig. 7), none of these locations offered climate stress conditions by either cold, heat, or drought to ladybird beetles occurrence. In general, only rainfall affected the population dynamic of predators, except for Chã Grande where the temperature also contributed to the estimates of the phenology of ladybird beetles throughout the year (fig. 5). All four locations had  $EI > 25$ , being considered suitable for the population growth of the ladybird beetles. Moreover, among the four locations, Petrolina had the lowest EI estimated,  $EI = 34$ , hence considered the location relatively least suitable for ladybird beetles occurrence. In contrast, Belo Jardim and Surubim had similar EI values, 61 and 66, respectively, and Chã Grande had the highest value of  $EI = 94$ .

### Interaction between predators

CLIMEX estimates for the interaction between *T. notata* and *C. montrouzieri* in the scenario of current climate conditions showed that the climate of South America is more suitable for *C. montrouzieri* establishment than for *T. notata* in most locations



**Figure 2.** CLIMEX map estimated for the potential distribution of *Cryptolaemus montrouzieri* in South America. The probability ranges are temperature intervals of the Ecoclimatic Index (EI). Unsuitable areas ( $EI = 0$ ), marginally suitable areas ( $1 \leq EI < 10$ ), suitable area ( $10 \leq EI < 25$ ), and strongly suitable areas ( $25 \leq EI < 100$ ).



**Figure 3.** CLIMEX map estimated for the potential distribution of *Tenuisvalvae notata* in South America. The probability ranges are temperature intervals of the Ecoclimatic Index (EI). Unsuitable areas ( $EI = 0$ ), marginally suitable areas ( $1 \leq EI < 10$ ), suitable area ( $10 \leq EI < 25$ ), and strongly suitable areas ( $25 \leq EI < 100$ ).

as seen in the substantial difference in EI values obtained for these species (fig. 8). Areas with a climate that favored *T. notata* (negative values) were rare in South America but were slightly more common in the Indonesian archipelago. In contrast, areas with strong positive values were common and included all Brazilian territory, being more suitable for *C. montrouzieri* (fig. 8).

### Discussion

The CLIMEX software proved to be a useful tool to forecast climatic suitability as seen in previous studies (Allen *et al.*, 1993; MacLeod *et al.*, 2002; Sutherst and Maywald, 2005). On this note, it is important to mention that many studies have addressed the effects of some of those factors on *C. montrouzieri*, but few have included *T. notata*. To our knowledge, this is the first study addressing the potential global distribution of these two predatory coccinellids, especially because both are good candidates for biological control programs. Both species studied here show preference and high predatory capacity upon mealybugs, either as larvae or as adults (Babu and Azam, 1987; Wu *et al.*, 2014; Barbosa *et al.*, 2014a, 2014b; Marques *et al.*, 2015). In fact, *C. montrouzieri* and *T. notata* overlap in their food niches

resulting in competition and intraguild predation, due to similarity in food diet, habitat, and the thermal requirement to development of both species (Ferreira *et al.*, 2020; Oliveira, 2020; Sá *et al.*, 2020).

Many exotic predatory ladybird beetles have been introduced in various regions of the world as part of classical biological control programs. Some factors favor the establishment of exotic species, such as the capacity to respond to alternative prey (Evans and Toler, 2007), high fecundity rates (Kajita and Evans, 2010), oviposition inhibition (Hodek and Michaud, 2008), and larger body size (Roy *et al.*, 2002). These factors are associated with better fitness and dispersal capacity, promoting the establishment and rapid spread of these ladybird beetles to other regions. For instance, *C. montrouzieri* has been used commercially in many biological control programs worldwide to control mealybugs and some aphids and psyllids (Pluke *et al.*, 2005; Gutierrez *et al.*, 2008; Mani and Krishnamoorthy, 2008). According to Fand *et al.* (2010), *C. montrouzieri* has a higher predatory performance than other coccinellids, and in comparison to *T. notata*, other studies have shown it has a higher predation rate and acts as intraguild predator, outcompeting this indigenous species (Oliveira, 2020).

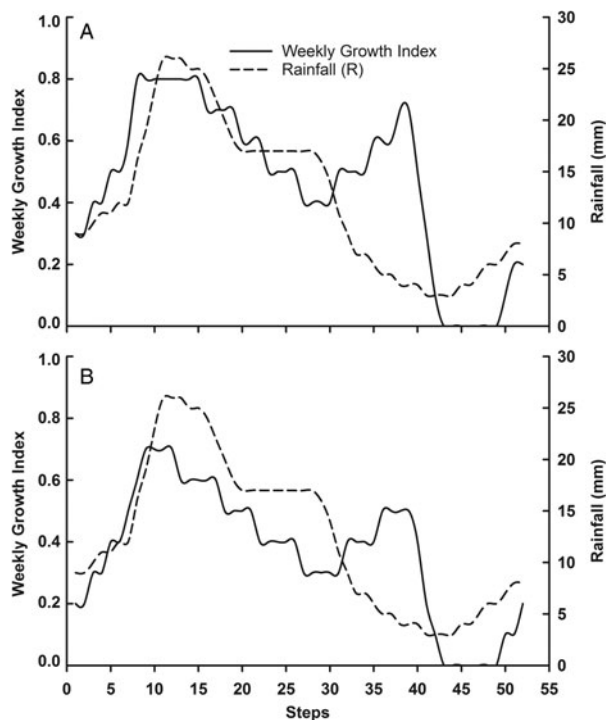


Figure 4. Phenology of *Cryptolaemus montrouzieri* (a) and *Tenuisvalvae notata* (b) in Belo Jardim, Pernambuco, Brazil (Lat.: -8.3446/Long.: -36.4134). Step (Weeks).

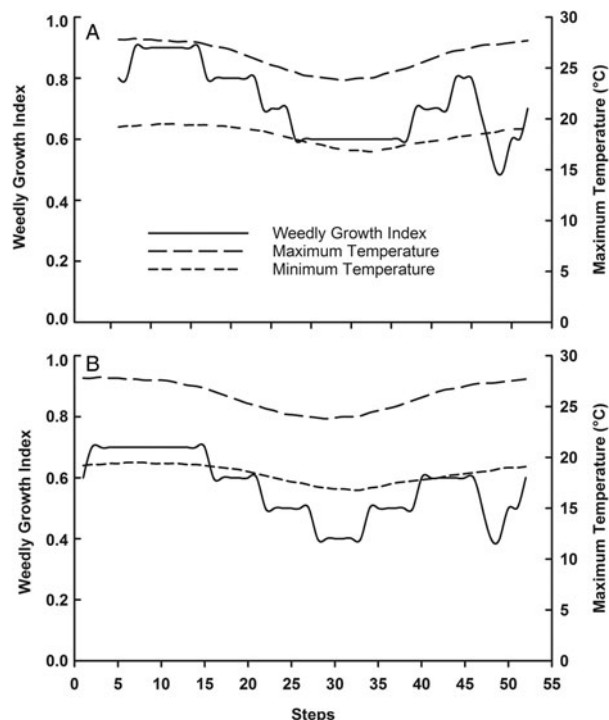


Figure 5. Phenology of *Cryptolaemus montrouzieri* (a) and *Tenuisvalvae notata* (b) in Chã Grande, Pernambuco, Brazil (Lat.: -8.2522/Long.: -35.4549). Step (Weeks).

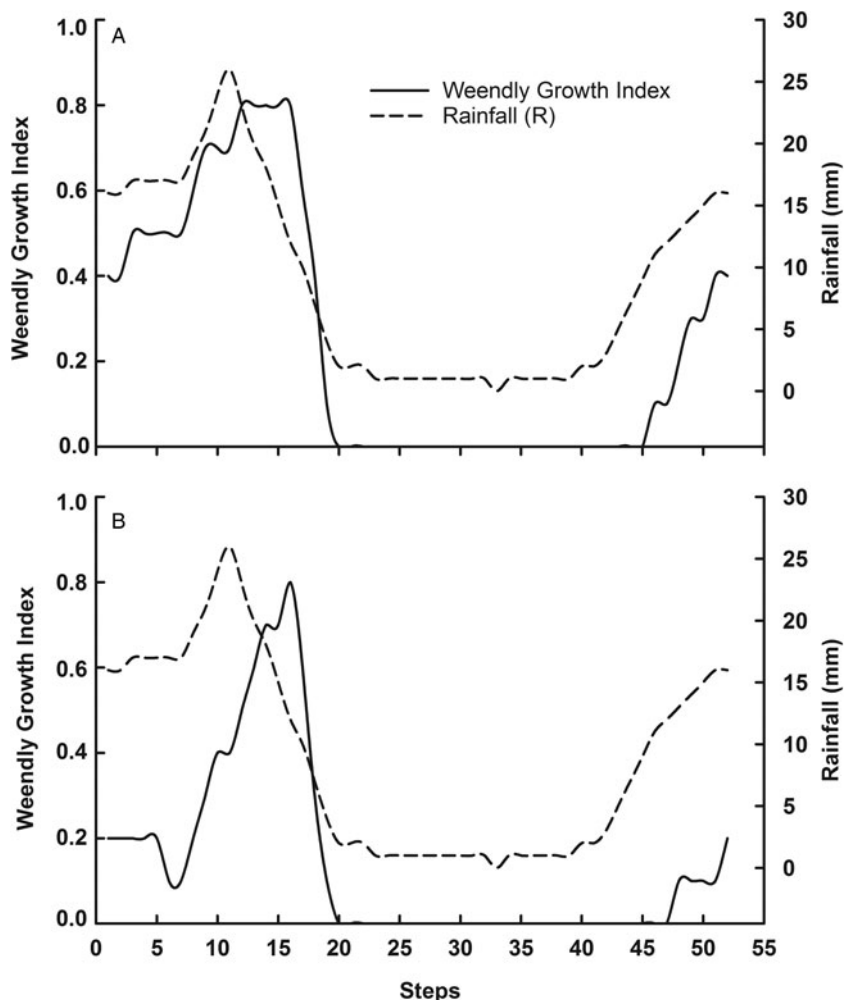
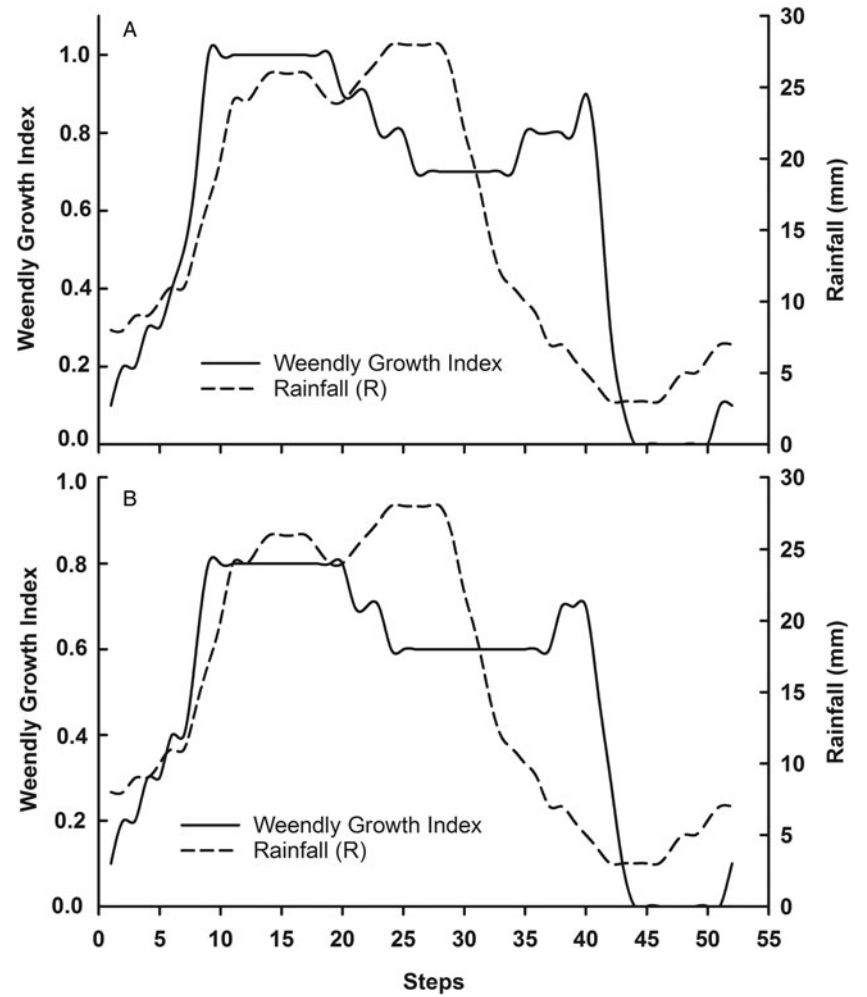
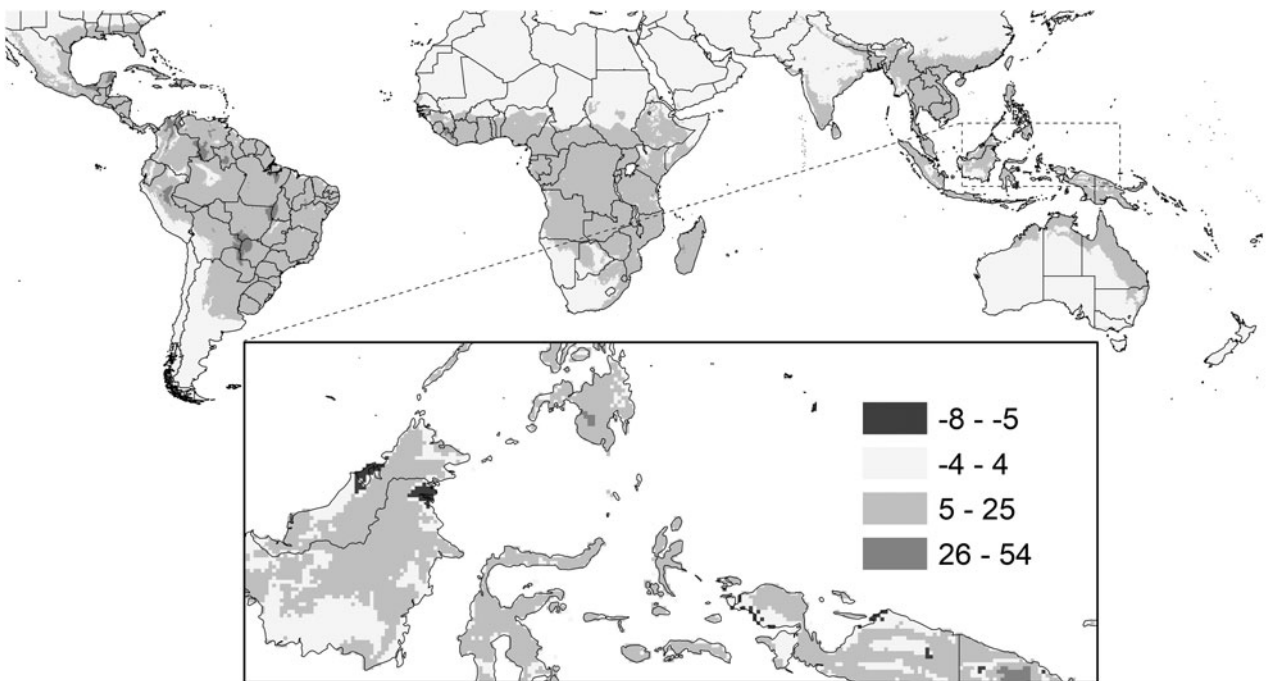


Figure 6. Phenology of *Cryptolaemus montrouzieri* (a) and *Tenuisvalvae notata* (b) in Petrolina, Pernambuco, Brazil (Lat.: -9.3948/Long.: -40.4962). Step (Weeks).



**Figure 7.** Phenology of *Cryptolaemus montrouzieri* (a) and *Tenuisvalvae notata* (b) in Surubim, Pernambuco, Brazil (Lat.: -7.8711/Long.: -35.7533). Step (Weeks).



**Figure 8.** CLIMEX map for the difference in the Ecoclimatic Index (EI) of *Tenuisvalvae notata* and *Cryptolaemus montrouzieri* in South America under the current climate condition. Areas with a strong positive value are more suitable for *T. notata*, being those places rare. Areas with strong negative values are more suitable for *C. montrouzieri*. Similar areas (EI difference between -4 and +4) are not likely to favor neither of the predator species.



The global forecast of climate suitability for *T. notata* and *C. montrouzieri* suggests the establishment of those species is possible in many parts of the world, especially near the Equator. The model also estimated that a larger part of South America, where *T. notata* is indigenous, is more suitable for the establishment of the exotic *C. montrouzieri*, including locations unsuitable for the indigenous species *T. notata*. Therefore, in various locations of the south hemisphere, where *C. montrouzieri* was introduced intentionally through classical biological control programs, its chances of survival are higher. In addition, the EI difference estimated for both coccinellids under the current scenario of climate condition shows that *C. montrouzieri* could have a broader distribution than *T. notata* in South America, possibly because *C. montrouzieri* has a wider thermal tolerance than *T. notata* (Ferreira *et al.*, 2020). Moreover, the model prediction was based on climate suitability as an indicator of potential global distribution. It does not mean that in all areas predicted as suitable, *C. montrouzieri* and *T. notata* are currently interacting. In fact, we cannot affirm how long it will take for *C. montrouzieri* to occupy suitable areas in South America, for instance. It may be possible that this never happens in some locations since other abiotic or biotic factors such as dispersal capability will shape distribution. But in areas where it already occurs, as in the state of Pernambuco, it may out-compete the native *T. notata* when food is scarce (Oliveira, 2020).

In areas of Europe, and North America (i.e. Canada and the US high plains), the model prediction is according to the current distribution of *C. montrouzieri* (Kairo *et al.*, 2013), and those areas have limited places for hibernation, and extreme climate conditions, such as freezing winters. This could explain why those areas have not registered the occurrence of *T. notata* and *C. montrouzieri*. Moreover, in part of Africa and the central region of Australia, those coccinellids are absent, probably due to the desert/arid climate condition in those locations, with low or no vegetation, which makes it difficult to the establishment of both prey and predators.

Sutherst *et al.* (2007) have suggested that CLIMEX seems to be more appropriate to estimate the distribution of species found in more restricted areas than those species that are cosmopolitan, being easier to relate the climate of the origin location and other continents. For *C. montrouzieri* and *T. notata* CLIMEX predictions are easily comparable to places where these predators have been introduced and established, such as South America and Africa, respectively, as well as other places where their occurrence have been cited in the literature. Therefore, observed data could compare model estimations for the global distribution of these predatory species out of their native range. For instance, outside their origin location, *C. montrouzieri* occurs in Africa, Asia, and America (Kairo *et al.*, 2013), and *T. notata* in Africa (Benim, Zambia) (Chakupurakal *et al.*, 1994; Dreyer, 1997a, 1997b), providing support for parameters estimated by the CLIMEX model, as EI values estimated for those locations were higher than 25, characterizing suitable places for both species.

Regarding the phenology of *C. montrouzieri* and *T. notata* throughout the year in four locations of the state of Pernambuco, Chã Grande, Petrolina, Surubim and Belo Jardim, representing different microclimate regions within the state, the model estimated  $EI > 25$  at all locations, suggesting climate suitability to the occurrence of *C. montrouzieri* and *T. notata*. Because the state of Pernambuco is located in the Northeast region of Brazil, climate change within the state is more related to precipitation than to temperature, except for places of high

altitude such as Chã Grande where the temperature tends to have larger variance and may reach lower digits during the winter season in comparison to the other locations studied here. Consequently, rainfall was the most limiting factor acting upon phenology of these predatory species in Petrolina, Surubim and Belo Jardim, except for Chã Grande where temperature fluctuation has also contributed to insect phenology throughout the year.

Finally, for the interaction between *C. montrouzieri* and *T. notata* in South America under the scenario of current climate condition, the model estimated that a larger area of this continent is more suitable for *C. montrouzieri* than for *T. notata*, which would be favored in rare locations, even though this is its native region. Thus, one can assume that when both predatory species co-occur in the same location, the result of the competition between them would be affected by the local climate condition, and may result in displacement of the indigenous species, as the introduced one is a better competitor and adapted to local conditions (Ferreira, 2019; Oliveira, 2020). In this context, many studies have suggested a reduction in the abundance of native coccinellids after the establishment of exotic species (Turnipseed *et al.*, 2014; Bahlai *et al.*, 2015; Diepenbrock *et al.*, 2016). However, it is important to be cautious when evaluating those effects. For instance, Harmon *et al.* (2007) did not find a consistent and significant decline in abundance of indigenous coccinellid species after the introduction of *Coccinella septempunctata* (L.) and *H. axyridis* in the USA and Canada. Also, Bahlai *et al.* (2015) looking at 24-year long data regarding coccinellid community in Michigan Southwest, showed that the impact of the exotic coccinellid species on indigenous ones varies with the degree of their interaction. This decline could be triggered by food competition among predatory species (dietary overlap with exotic species), habitat compression where exotic species are expected to dominate in crop areas whereas native species are pushed to natural or semi-natural habitats, intraguild predation, but also could be increased by the local climate conditions.

In conclusion, this study suggests that both coccinellids *T. notata* and *C. montrouzieri* could experience a climate suitable for establishment in areas of a warmer climate, such as Equatorial and Tropical zones. In addition, most of South America is more suitable for *C. montrouzieri* than for *T. notata* according to the EI. In addition, beyond temperature and precipitation, other biotic interactions with prey, host plants, and other predators may regulate insect phenology and determine the success of biological control programs in different locations. For *T. notata* much more remains to be learned as little is known about its distribution, ecology, and predatory capacity within its native range. Further research is needed to address those questions and how exotic species like *C. montrouzieri* could affect the native *T. notata* regarding its distribution and potential use in biological control in Brazil.

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