# False Codling Moth

**_Thaumatotibia leucotreta_ (Lepidoptera: Tortricidae)**

Phenology/Degree-Day and Climate Suitability Model Analysis for USPEST.ORG
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**Summary**

A phenology model and temperature-based climate suitability model for the false codling moth (FCM), *Thaumatotibia leucotreta* (Meyrick), was developed using data from available literature and through modeling in CLIMEX v. 4 (Hearne Scientific Software, Melbourne, Australia; Kriticos et al. 2015) and DDRP (Degree-Days, Risk, and Pest event mapping; under development for uspest.org).

## Introduction

*Thaumatotibia leucotreta* is a pest of more than 100 host plants, including all *Citrus* spp. and more than 40 other crops of economic importance in the US including corn, cotton, grapes, peaches, eggplant, and peppers. Its potential economic impact rating is "High" owing to its highly polyphagous habits and its potential ability to thrive in many climates in the US (USDA climatic zones 7b through 10a; Vennette et al. 2003; Gilligan et al. 2011). Native to Ethiopia and sub-Saharan Africa, *T. leucotreta* is not currently established in the US but it was intercepted over 1500 times at 34 ports of entry between 1984 and 2006 (Venette et al. 2003; Gilligan et al. 2011). It is predominantly a warm climate pest so development is limited by cold temperatures. As much as 20% of the country could be at risk of introduction owing to its suitable climate and high availability of host plants (Venette et al. 2003).

## Phenology modeling

*Objective.*—We aimed to estimate rates and developmental degree-days for *T. leucotreta* by solving for a best overall common threshold and corresponding developmental degree-days (DD) using data from available literature.

*Temperature developmental thresholds*.—This is a summary of the spreadsheet analysis that is available online (https://uspest.org/wea/Thaumatotibia_leucotreta_model.pdf). A summary of temperature developmental thresholds and durations is reported in Table 1. We re-interpreted temperature vs. development rate data from lab development studies of *T. leucotreta* eggs (Daiber 1979a), larvae (Daiber 1979b), pupae (Daiber 1979c), and adults (Daiber 1980) at three temperatures. These studies suggested a low threshold of *ca.* 11.7°C for eggs, 11.9 to 12.5°C for larval instars, 11.9°C for pupae, and 12.2°C for adults. We used the x-intercept method with forcing through the x-intercept to estimate the low threshold and DD requirements for major stages of the species, which resulted in a lower temperature threshold (LDT) of 11.7°C or 53°F.

We used an upper development threshold (UDT) of 38°C based on a study by Terblanche et al. (2017), which reported a critical thermal maximum of *ca.* 42°C for both adults and larvae, and a significant increase in mortality of adults after 40°C. The UDT is likely to be at least slightly lower than these values.

*Development in degree days*.—At a lower threshold of 11.7°C, egg, larval, pupal, egg-to-adult and pre-oviposition DD requirements were 71, 155, 175, 400, and 17  DDCs, respectively. The resulting summary for degree-day requirements is reported in Table 1. The pupa is the major overwintering stage (Malan et al. 2018). We estimated DDs of first and peak adult spring flight by computing degree-days from Jan 1- Mar 1 at sites where these events were described in South African citrus studies (Stotter 2009; Citrus Research Inst. 2017; Malan et al. 2018). The model currently is based on first flight at *ca*. 160 DD and first peak flight at *ca.* 220 DD for the overwintering pupal and adult generation. A generation time of 484 DD (total from egg to 50% oviposition) was used to estimate first and peak flight for each subsequent generation.

*Emergence parameters*.—We assumed seven cohorts emerged in the spring according to a normal distribution, with an average emergence of 220 DDCs (range = 140–280 DDCs; Table 1). These values were chosen because peak flight of the OW generation was estimated as 220 DDCs, but moths may emerge as early as 160 DDCs. According to monitoring data collected by the Citrus Research Institute (2017), it appears that catches decline fairly rapidly after peak flight (see Fig. 12 of their report), so we set the upper limit to 280 DDCs (i.e., there is not a long tail).

**Climate suitability modeling**

*Objective.*—The aim of these analyses was to determine which climate stress parameters in DDRP (chill stress temperature threshold, heat stress threshold, and chill and heat stress unit limits) resulted in map outputs most similar to a 1) CLIMEX model generated for this study; 2) correlative niche models by A. West (unpublished data); and 3) a previously published NAPPFAST model. DDRP models used a PRISM data set of daily temperature data from 1960 to 1990, which matches the gridded weather data interval used for the CLIMEX analysis. A summary of DDRP and CLIMEX parameters used for climate suitability modeling is reported in Tables 1 and 2, respectively.

*CLIMEX model*.—We produced a CLIMEX model for *T. leucotreta* and used the model for its native range (Africa; Fig. 1) to fine-tune CLIMEX parameters (Table 2). We obtained 97 locality records for Africa from GBIF.org (10 June 2019, GBIF Occurrence Download https://doi.org/10.15468/dl.nie2ti) and the literature. We then adjusted CLIMEX parameters to ensure that the majority of these locality records fell within areas with relatively high climatic suitability (as measured by the ecoclimatic index).

The temperature parameter values (DV0, DV1, DV2, DV3) were based on developmental thresholds estimated for DDRP, the literature, and by calibrating them so that (most) Africa records fell within suitable (EI > 20) areas (Fig. 1). Data on moisture requirements for *T. leucotreta* are lacking, so moisture index parameters where relaxed and heat stress parameter values were then calibrated to reach the same overall CLIMEX distribution shown in Fig. 1. Resulting moisture stress parameters SM0, SM1, SM2, and SM3 were 0.05, 0.25, 0.8, and 1.0, respectively. Chill and heat stress parameters are described below.

*Chill stress parameters*.—We applied a chill stress threshold of –1ºC in both CLIMEX and DDRP. This value is consistent with three data sources: 1) a correlative niche modeling study by A. West (unpublished) revealed that FCM occurrence increased in areas where the minimum temperature of the coldest month is between –1 and 20° C; 2) a previously published NAPPFAST model (NAPPFAST, 2003) for *T. leucotreta* applied a lower threshold of –1ºC; and 3) a lab study by Stotter et al. (2009) reported that the lower lethal temperature (that results in 50% mortality after 10 hours) for adults was –0.5ºC. Two other laboratory studies reported even lower lethal temperatures for adults and larvae

(Boardman et al. 2012; Terblanche et al. 2017), but they measured mortality only at temperatures lower than −4ºC.

We used our CLIMEX model (Fig. 4), an ensemble map of correlative niche models (ensemble model) by A. West (Fig. 5b), and the NAPPFAST model (Fig. 5c) to assist with defining chill stress unit limits for *T. leucotreta* in DDRP. The ensemble model was derived by identifying areas of overlap between five models that were generated with different correlative algorithms (generalized linear model, boosted regression trees, multivariate adaptive regression spline, Random Forests, and Maxent; Fig. 5b).

The northern range limit was the main factor that differed between the CLIMEX, ensemble, and NAPPFAST models. CLIMEX predicted suitable conditions (EI > 20) slightly farther north than the ensemble and NAPPFAST models, particularly along the eastern seaboard (e.g., in North and South Carolina). However, one of the models (model 1) in West's ensemble model predicted suitable conditions in areas north of *ca*. 32.0º N (Fig. 5b), consistent with CLIMEX. Additionally, the NAPPFAST model predicted that the species may occur farther north if it could survive being exposed to minimum temperatures below −1ºC and an average daily temperature below 10ºC for 25 days (Fig. 5c). To account for uncertainty in the northern range limit of *T. leucotreta* in DDRP, we defined the second chill stress limit (chillstress_units_max2) such that areas under moderate stress exclusion roughly corresponded to areas that differed between the three other models.

*Heat stress parameters*.—We applied a heat stress threshold of 40ºC in both CLIMEX and DDRP. Johnson and Neven (2010) reported that the upper lethal temperature at which 50% of the population died was 41−45ºC for eggs (after 1.5−2.5 hours) and 38−45ºC for larvae (after 2−2.5 hours). In another study, mean larval survival dropped off between 48 and 52ºC, whereas mean adult survival dropped off between 40 and 44ºC (Terblanche et al. 2017). Thus, immature stages apparently have a higher heat stress threshold. We chose to use the lower threshold of 40ºC because populations would be unlikely to persist if adult survival is low.

*Results*.—CLIMEX and DDRP identified chill stress as the major factor shaping the distribution of *T. leucotreta* (Fig. 2), while heat stress excluded the species only from some very small areas of southwestern Arizona and southeastern California (Fig. 3). In general, the DDRP climate suitability model predicted suitable conditions (i.e., not excluded) in the same areas as the CLIMEX, ensemble, and NAPPFAST models (Figs. 4 and 5), although some slight differences were detected. In contrast to other models, CLIMEX predicted the absence of the species in coastal Louisiana and Mississippi due to wet stress (results not shown). The DDRP and NAPPFAST model predicted suitable conditions throughout the west coast, whereas the CLIMEX and most models in the ensemble model did not predict high suitability in this region.

**Suggested applications**

The DDRP model may be run to test where *T. leucotreta* may become established and reproduce in CONUS under past, current and future climate conditions, and to estimate the dates when specific pest events will occur. For example, one can estimate the date of adult flight for one or more generations to guide APHIS supported Collaborative Agricultural Pest Survey (CAPS) programs. We provide two example maps using 2012 PRISM data (the hottest year on record for CONUS) showing (a) the date of first egg laying by females with severe climate stress exclusions (Fig. 6), and (b) potential voltinism (number of generations; Fig 7).

**Improvements needed**

More locality records are needed to adequately identify areas that are known to have suitable climate for *T. leucotreta*. If such data are available, then additional sensitivity analyses could be conducted to identify optimal parameter values for CLIMEX models. Data on the impacts of moisture on development and survival are needed to inform moisture stress parameters in CLIMEX. The DDRP and CLIMEX models presented here do not incorporate irrigation data, and so may underestimate the species' distribution. For example, certain desert areas such as southeastern New Mexico are predicted to be unsuitable according to both models (Fig. 4), but irrigated cropland there (e.g., for peppers) could provide suitable habitats.

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## Tables and Figures

**Table 1**. DDRP parameter values for *Thaumatotibia leucotreta*.

| Parameter | Code | Value |
|---|---|---|
| Lower developmental thresholds (°C) | | |
| Egg | eggLDT | 11.7 |
| Larvae | larvaeLDT | 11.7 |
| Pupae | pupaeLDT | 11.7 |
| Adult | adultLDT | 11.7 |
| Upper developmental thresholds (°C) | | |
| Egg | eggUDT | 38.0 |
| Larvae | larvaeUDT | 38.0 |
| Pupae | pupaeUDT | 38.0 |
| Adult | adultUDT | 38.0 |
| Stage durations (°C degree-days) | | |
| Egg | eggDD | 71 |
| Larvae | larvaeDD | 155 |
| Pupae | pupDD | 175 |
| Adult | adultDD | 83 |
| Pest events (°C degree-days) | | |
| Egg event | eggEventDD | 71 |
| Larva event | larvaeEventDD | 77 |
| Pupa event | pupaeEventDD | 145 |
| Adult event | adultEventDD | 17 |
| Chill stress | | |
| Chill stress temperature threshold (°C) | chillstress_threshold | –1 |
| Chill degree-day (°C) limit when most individuals die | chillstress_units_max1 | 25 |
| Chill degree-day (°C) limit when all individuals die | chillstress_units_max2 | 250 |
| Heat stress | | |
| Heat stress temperature threshold (°C) | heatstress_threshold | 40 |
| Heat stress degree-day (°C) limit when most individuals die | heatstress_units_max1 | 75 |
| Heat stress degree-day (°C) limit when all individuals die | heatstress_units_max2 | 150 |
| Cohorts | | |
| Avg. degree-days (°C) to OW adult spring 1st flight | distro_mean | 220 |
| Var. in degree-days (°C) to OW adult spring 1st flight | distro_var | 500 |
| Minimum degree-days (°C) to OW adult spring 1st flight | xdist1 | 140 |
| Maximum degree-days (°C) to OW adult spring 1st flight | xdist2 | 280 |
| Shape of the distribution of degree-days (°C) to OW adult spring 1st flight | distro_shape | normal |

**Table 2**. Parameter values used to produce a CLIMEX model for *Thaumatotibia leucotreta*

| CLIMEX parameter | Code | Value |
|---|---|---|
| Temperature | | |
| Lower temperature threshold (°C) | DV0 | 11.7 |
| Lower optimal temperature (°C) | DV1 | 18 |
| Upper optimal temperature (°C) | DV2 | 35 |
| Upper temperature threshold (°C) | DV3 | 40 |
| Degree-days per generation (°C days) | PDD | 450 |
| Moisture | | |
| Lower soil moisture threshold | SM0 | 0.05 |
| Lower optimal soil moisture | SM1 | 0.15 |
| Upper optimal soil moisture | SM2 | 0.8 |
| Upper soil moisture threshold | SM3 | 1 |
| Cold stress | | |
| Cold stress temperature threshold (°C) | TTCS | −1 |
| Cold stress temperature rate ($week^{-1}$) | THCS | −0.05 |
| Heat stress | | |
| Heat stress temperature threshold (°C) | TTHS | 40 |
| Heat stress temperature rate ($week^{-1}$) | THHS | 0.0002 |
| Dry stress | | |
| Dry stress threshold | SMDS | 0.05 |
| Dry stress rate ($week^{-1}$) | HDS | −0.00005 |
| Wet stress | | |
| Wet stress threshold | SMWS | 1.1 |
| Wet stress rate ($week^{-1}$) | HWS | 0.004 |

**Fig. 1.** Climate suitability model for *Thaumatotibia leucotreta* (FCM) in its native range (Africa) produced by CLIMEX. Hollow black circles depict locality records for the species gathered from GBIF and the literature. A higher ecoclimatic index (EI) indicates greater climatic suitability.

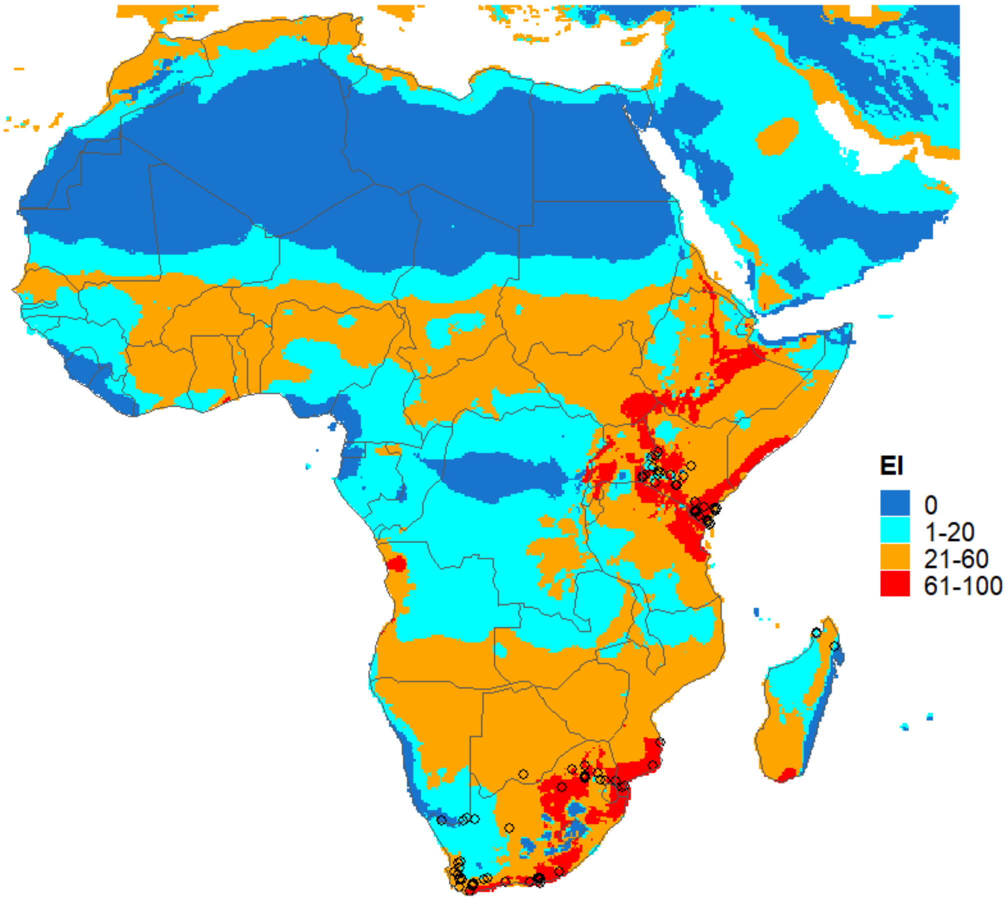

**Fig. 2.** Maps of cold/chill stress units for *Thaumatotibia leucotreta* (FCM) produced by (a) CLIMEX (cold stress temperature threshold, TTCS = −1ºC) and (b) DDRP (chill stress temperature threshold = −1ºC). DDRP chill stress units have been scaled from 0 to 100 to match the scale used by CLIMEX. Reference climate data for DDRP were from 1960−1990 Normals (matched to available CLIMEX data). The pink and black lines in (b) depict the chill stress unit limits 1 and 2 (5 and 125 CSUs, respectively; Table 1).

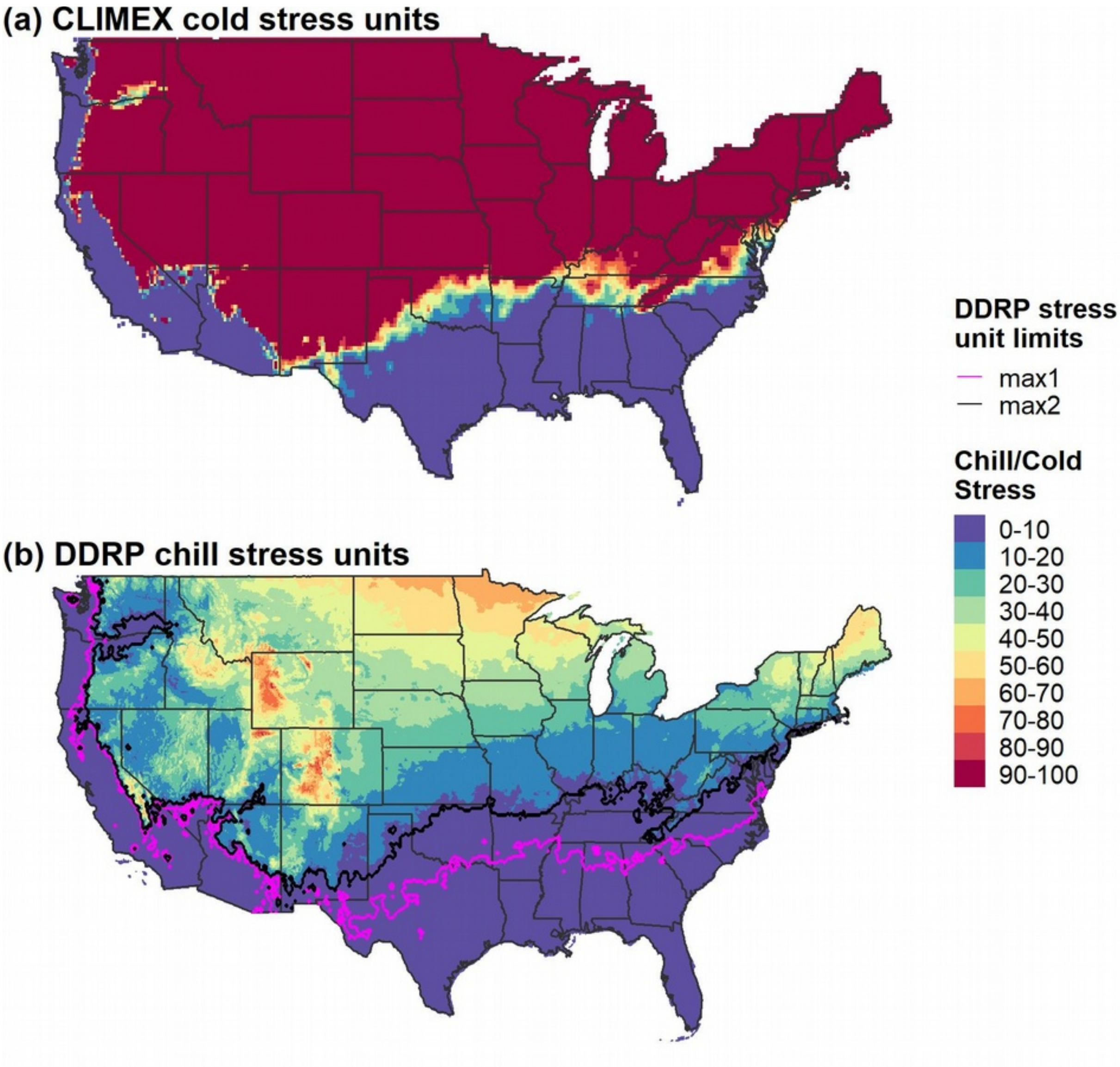

**Fig. 3.** Maps of heat stress units for *Thaumatotibia leucotreta* (FCM) produced by (a) CLIMEX (heat stress temperature threshold, TTHS = 40ºC) and (b) DDRP (heat stress temperature threshold = 40ºC). DDRP heat stress units have been scaled from 0 to 100 to match the scale used by CLIMEX. Reference climate data for DDRP were from 1960–1990 Normals (matched to available CLIMEX data). The pink and black lines in (b) depict the heat stress unit limits 1 and 2 (75 and 150 CSUs, respectively; Table 1).

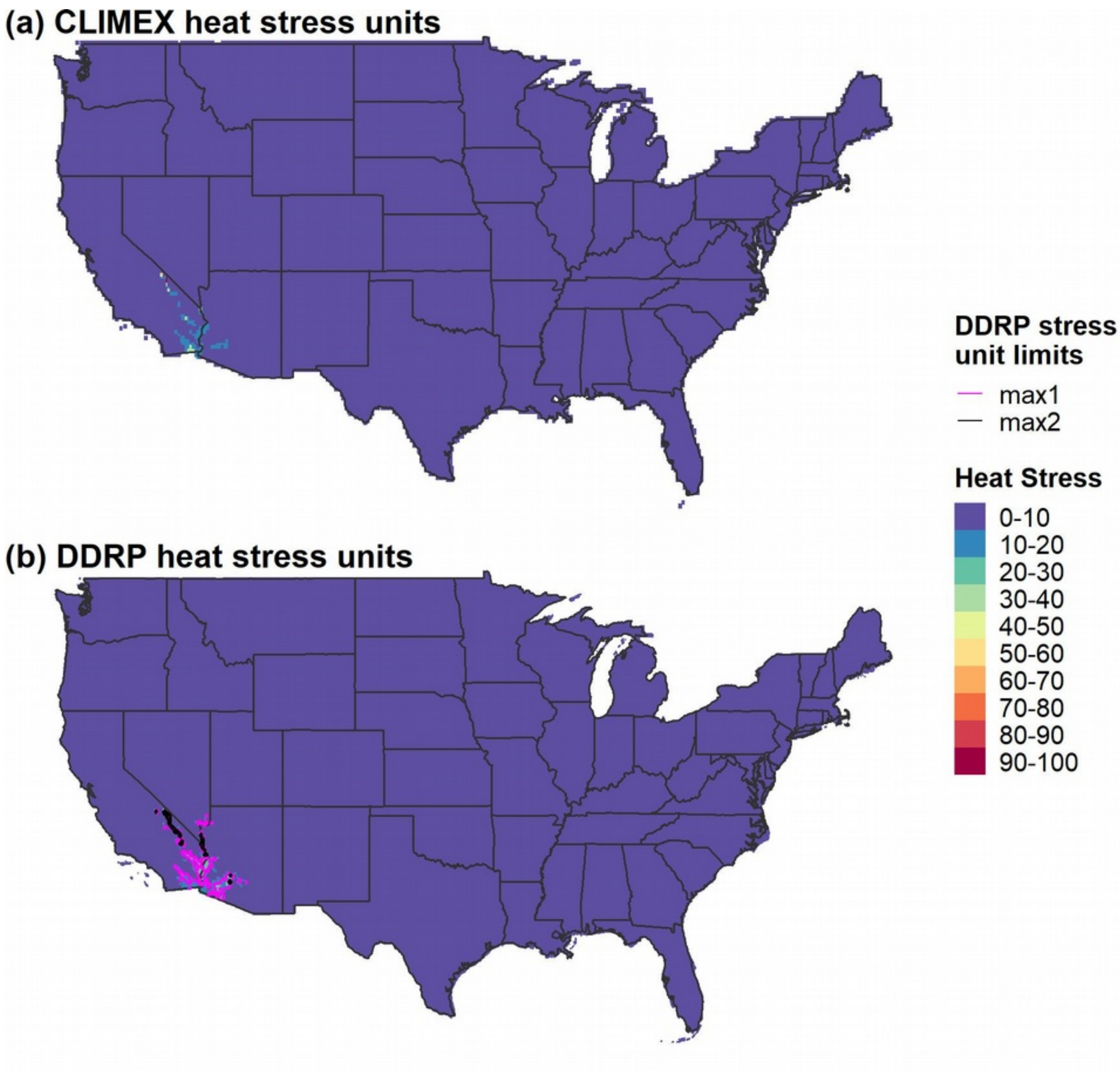

**Fig. 4.** Climate suitability models for *Thaumatotibia leucotreta* (FCM) in CONUS produced by (a) CLIMEX and (b) DDRP. DDRP measures exclusion status of the species based on chill and heat stress units (all stress exclusion). Both models applied a cold/chill stress threshold of −1ºC and a heat stress threshold of 40ºC. Reference climate data for DDRP were from 1960−1990 Normals (matched to available CLIMEX data).

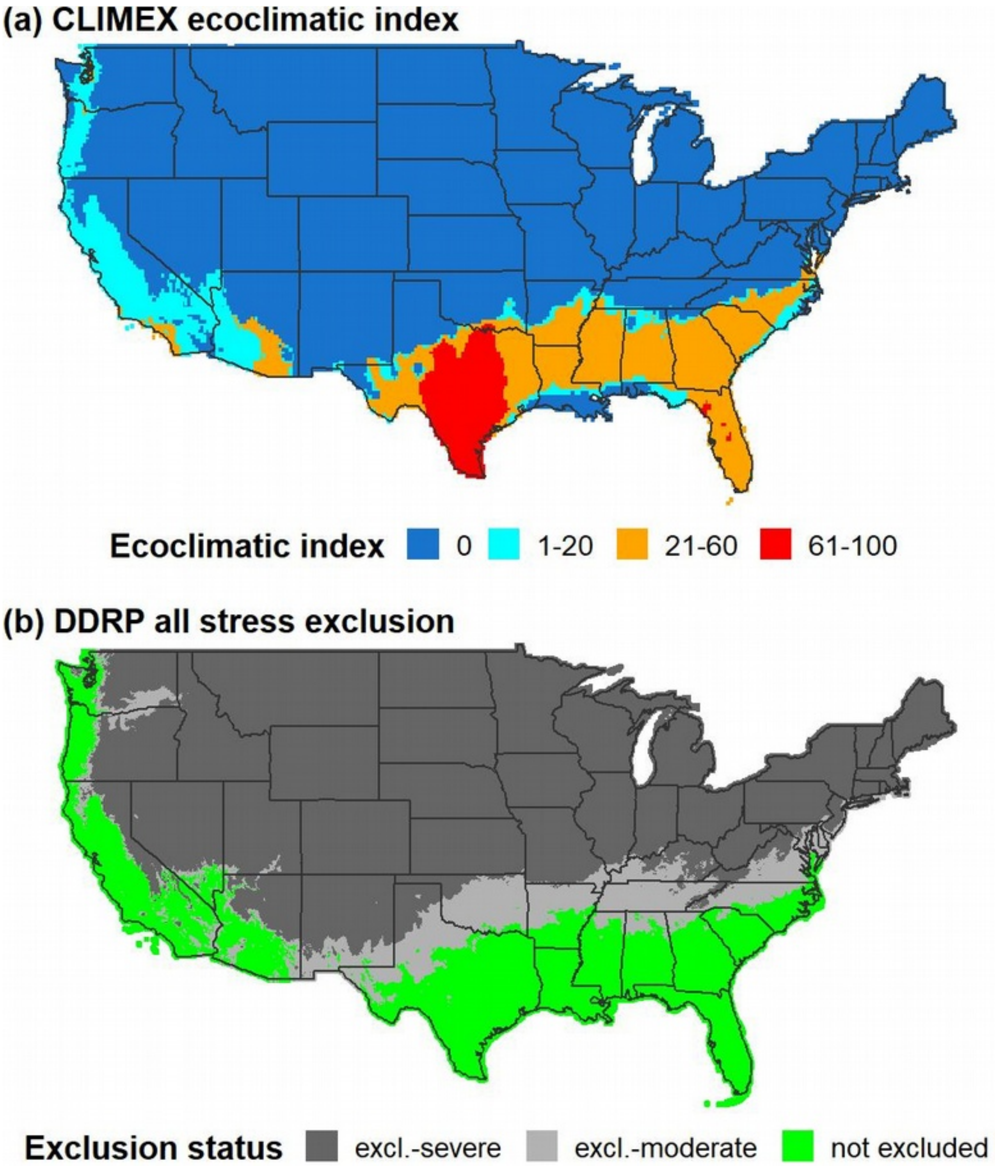

**Fig. 5.** Map of (a) climate suitability for *Thaumatotibia leucotreta* (FCM) produced by DDRP (reference climate data for DDRP were from 1960–1990 Normals) compared to: (b) an ensemble map of five climatic suitability models (A. West, unpublished data), and (c) a map of estimated number of generations generated by NAPPFAST. Areas of potential exclusion in the NAPPFAST map are where minimum temperature is below –1ºC and average daily temperature is below 10ºC for 25 (light gray) and 50 (dark gray) or more days.

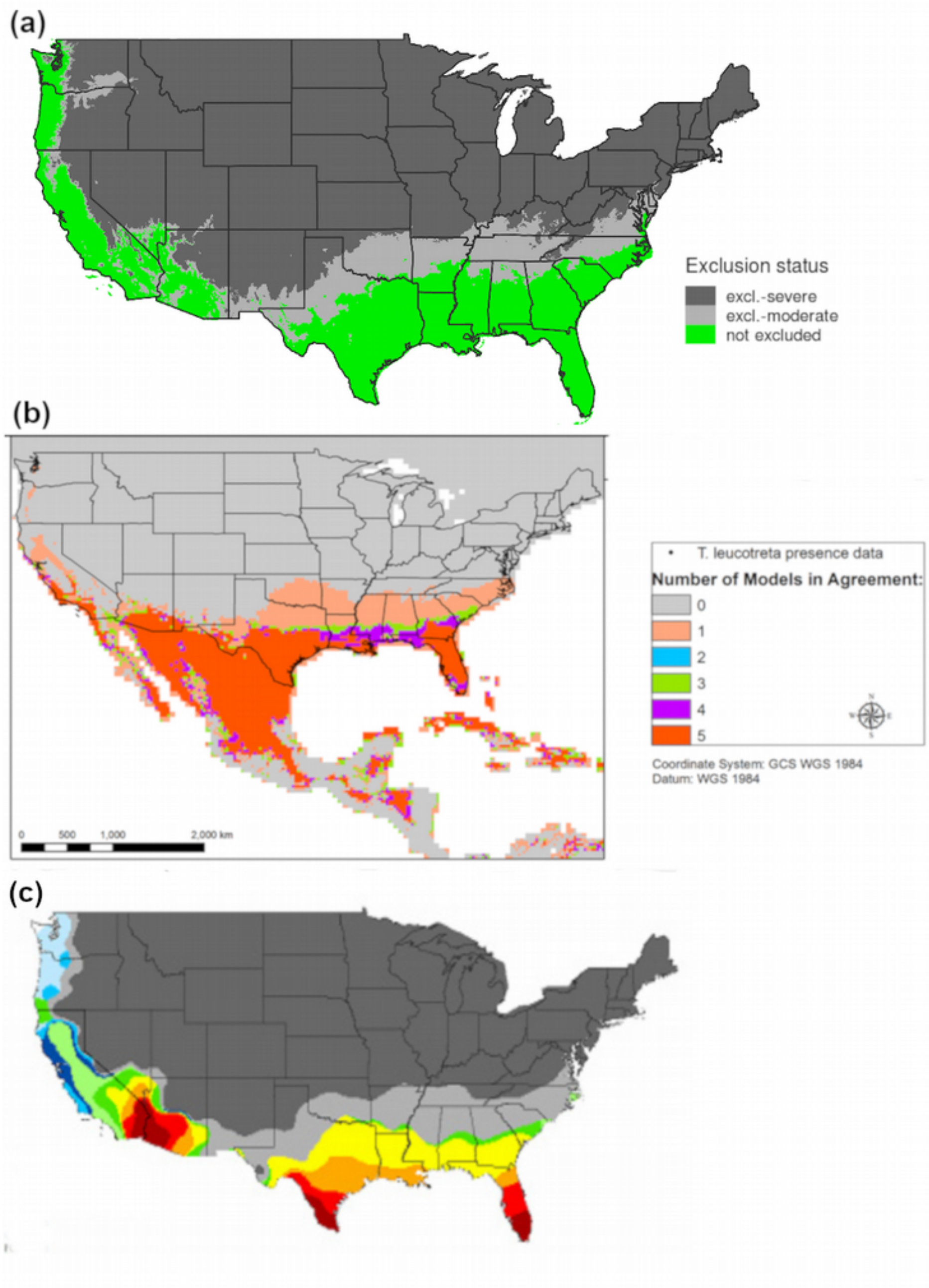

**Fig. 6.** Map depicting the date of first egg laying by females of the overwintering generation with severe climate stress exclusion for *Thaumatotibia leucotreta* (FCM) for 2012 (based on chill and heat stress units) produced by DDRP.

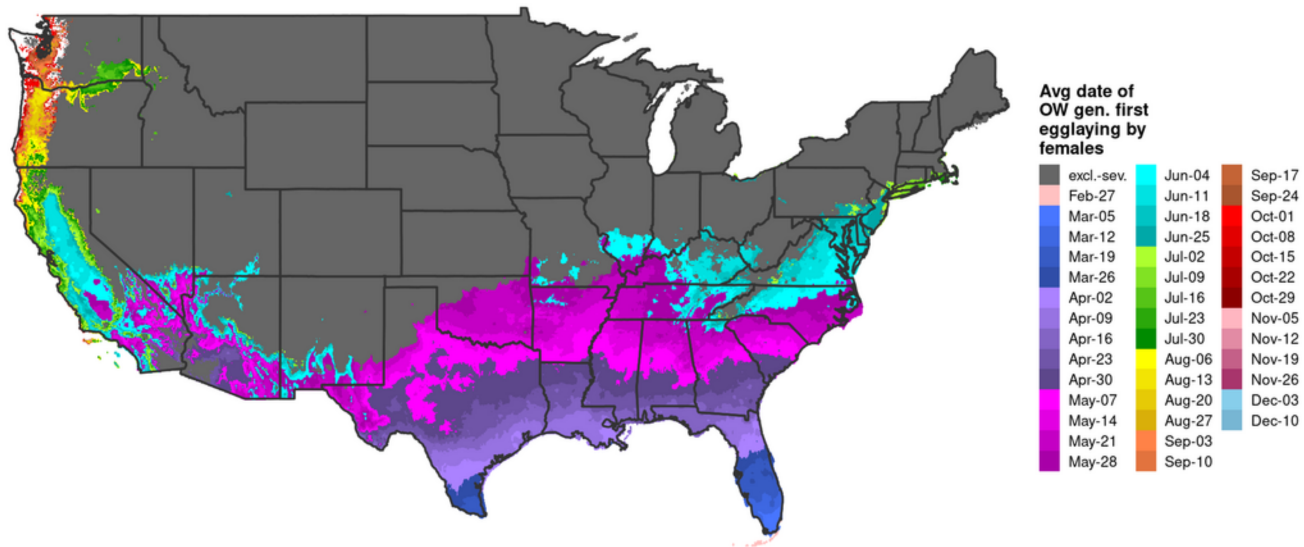


**Fig. 7.** Map showing the voltinism (number of generations) of *Thaumatotibia leucotreta* (FCM) with severe climate stress exclusion (based on chill and heat stress units) for 2012 produced by DDRP.