Tomato Leafminer

Tuta absoluta (Lepidoptera: Gelechiidae)

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 Tomato leafminer (TABS), *Tuta absoluta* (Meyrick), was developed using data from available literature and through modeling in CLIMEX v. 4 (Hearne Scientific Software, Melbourne, Australia) and DDRP (Degree-Days, Risk, and Pest event mapping; under development for uspest.org).

Introduction

Tuta absoluta (Lepidoptera: Gelechiidae) is a serious pest of tomato crops in Europe, Africa, western Asia, and South and Central America (Biondi et al. 2017). Native to the Peruvian central highlands, it spread throughout Latin America during the 1960s and then invaded Africa, Europe, and Asia (Biondi et al. 2017). *Tuta absoluta* may reduce tomato crop yields by as much as 100% if unmanaged, and will attack other Solanaceous crops including potato, eggplant, and European black nightshade (CABI 2019). The pest has caused increases in tomato prices, bans on the trade of tomato, increased synthetic insecticide applications, increases in the cost of crop protection, and disruptions to IPM programs for other tomato pests (Biondi et al. 2017, CABI 2019). Previous climate suitability modeling studies have indicated that parts of the U.S. are at a high risk of invasion by *T. absoluta* (Tonnang et al. 2015, Santana et al. 2019).

Phenology model

Objective.—We aimed to estimate rates and degree days of development in *T. absoluta* by solving for a best overall common threshold and corresponding developmental degree days (DDs) using data from available literature. While the DDRP platform allows for different thresholds for each stage, the site-based phenology modeling tools at uspest.org require common thresholds. Building the model for both platforms keeps models simpler and able to be cross-compared. For example, a prediction mapped via DDRP can be confirmed using any of the degree-day calculators at uspest.org, such as https://uspest.org/dd/model_app, which is mobile-device capable and can be readily run in the field.

Temperature developmental thresholds.—This is a summary of the spreadsheet analysis that is available online (https://uspest.org/wea/Tuta_absoluta_model.pdf). We re-interpreted temperature vs. development rate data from numerous laboratory and field studies including Cherif et al. (2019), Mahdi and Doumandji (2014), Krechemer and Foerster (2015), Barrientos et al. (2000), Erdoğan and Babaroglu (2014), Sylla et al. (2019), Pereyra and Sánchez (2006), Asma and Kaouthar (2017), and Rasheed et al. (2018). For lab studies conducted at multiple temperatures, we used linear regression (x-intercept method) with forcing through the x-intercept to estimate the low threshold and DD requirements for major stages of the species (Campbell et al. 1974). From these works, we solved for a common lower temperature threshold of 7.78°C common to eggs, larvae, pupae and egg to adult. The results all had high R-sq values, ranging from a low of 0.877 to a high of 0.9999, with an overall mean of 0.976. For field studies including Asma and Lebdi-Grissa (2017) [Table 1], we estimated degree-days per generation based on reported flight peaks and monthly average temperatures.

Development in degree days.—Results including averages, standard deviations, and C.V.s for major stages from the numerous studies are cited above are reported in Table 1. At a lower threshold of 7.78°C, egg, larval, pupal, egg-to-adult and pre-oviposition DD requirements were 75, 214, 138, 442, and 25 DDs, respectively. Estimated generation time averaged 478 DDs, which assumes that population peaks occur around 20% of the full oviposition interval which was 166 DDs.

Emergence parameters.—We assumed seven cohorts emerged in the spring according to a normal distribution, with an average emergence of 25 DDCs (range = 1–60 DDCs; Table 2). We assumed that adults overwinter and can begin laying eggs after the nominal pre-oviposition period, which is 25 DDCs, although a lower limit of 1 DDC accommodates earlier activity. Peak spring egg-laying occurs at *ca.* 58 DDCs.

Climate suitability model

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 CLIMEX model based on Santana et al. (2019). 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 are reported in Tables 2 and 3, respectively.

CLIMEX climate suitability model

Several studies have generated a CLIMEX model for *T. absoluta* to estimate climatic suitability and its potential spread at regional and global scales (Desneux et al. 2010, Tonnang et al. 2015, Xian et al. 2017, Santana et al. 2019). With the exception of the chill stress threshold and rate, we used the parameter values of Santana et al. (2019) because they validated their model based on occurrence data in South America and known areas of absence in Brazil (Table 3). Additionally, they used 148 world-wide occurrences to verify that the model accurately predicted climatic suitability (91% of the localities were in agreement with predicted suitability). Santana et al. (2019) reported that adding hot-wet stress as a variable resulted in the most accurate predictions of the known absence of *T. absoluta* from hot and wet areas in South America.

We modified the cold stress threshold (TTCS) and rate (THCS) in the CLIMEX model of Santana et al. (2019). The authors justify their value of 7°C by citing Martins et al. (2016); however, this study did not measure development or survival of insects at this temperature. We applied a TTCS value of 4°C based on two laboratory studies that investigated the relationship between temperature and mortality in *T. absoluta* (Van Damme et al. 2015, Kahrer et al. 2019). The cold stress rate (THCS) was adjusted to ensure that most field population records from Eurasia were included in areas predicted to be suitable (Fig. 1).

It is important to note that we used only field population records when calibrating a new cold stress threshold and rate for the *T. absoluta* CLIMEX model. Consequently, our model could underestimate the species' range in parts of the U.S. where its food source is grown in greenhouses over the winter. Greenhouses provide food and warm conditions that allow populations in cold regions (e.g., Belgium, United Kingdom) to persist year-round (Biondi et al. 2017).

DDRP climate suitability model

Following Santana et al. (2019), we assumed that areas in CONUS with EI > 30 are highly suitable, areas with 20 > EI > 0 have low suitability, and areas with EI = 0 are unsuitable. We used these definitions as a basis for defining chill and heat stress limits in DDRP (Figs. 2 and 3): areas under moderate stress exclusion in areas have low suitability according to CLIMEX, and areas under severe stress exclusion have EI = 0.

Our climate suitability model calibrations in DDRP produced estimates of chill stress and heat stress that were similar to those of CLIMEX (Figs. 2 and 3). The DDRP model applied a lower chill stress threshold than CLIMEX (2 vs. 4°C, respectively), and a higher heat stress threshold (40 vs. 35°C). The heat stress limits in DDRP were set very high because CLIMEX predicted high suitability in the Southwest despite high levels of heat stress there.

DDRP's climate suitability model predictions were very consistent with CLIMEX (Fig. 4), with two exceptions. According to CLIMEX, hot-wet stress lowered suitability for nearly all of southern Florida and some other small areas along the Gulf coast (Fig. 5). In contrast, DDRP did not exclude the species from any of these areas. In the West, DDRP predicted an overall greater area of suitability than CLIMEX. In particular, it did not exclude the species from coastal Oregon and Washington, whereas CLIMEX predicted low or zero suitability there.

Suggested applications

The DDRP model may be run to test where *T. absoluta* 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 first generation females (Fig. 6), and (b) potential voltinism (number of generations per year; Fig. 7) with severe climate stress exclusions. Predictions of egg laying could be useful for timing the release of biocontrol insects that prey on eggs and larvae, for example.

Improvements needed

Accounting for both wet and dry stress in DDRP will be important for accurately modeling the potential distribution of *T. absoluta* in the Southeast. Additionally, collecting more field population records in Eurasia could potentially help to further refine the cold stress threshold and rate, and the nature of overwintering population structure at cooler parts of this insects' range.

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Table 1. Summary of developmental requirements of *Tuta absoluta* in DDCs. The lower threshold is 7.78°C. Generation time includes all stages with an assumed 20% of the oviposition (OV) stage.

Stage:	Egg	Larvae	Pupae	Egg-to-Adult	Pre-OV	OV	Generation Time
N (no. of studies)	7	8	7	8	3	5	7
Average	75	211	138	442	25	166	478
St. Dev.	13.6	21.4	18.5	41.3	2.5	27.7	11.1
C.V.	18.2	10	13.5	9.4	10	16.6	2.3

Table 2. DDRP parameter values for *Tuta absoluta*.

Parameter	Code	Value
Lower developmental thresholds (°C)		
Egg	eggLDT	7.78
Larvae	larvaeLDT	7.78
Pupae	pupaeLDT	7.78
Adult	adultLDT	7.78
Upper developmental thresholds (°C)		
Egg	eggUDT	35
Larvae	larvaeUDT	35
Pupae	pupaeUDT	35
Adult	adultUDT	35
Stage durations (°C degree-days)		
Egg	eggDD	75
Larvae	larvaeDD	214
Pupae	pupDD	138
Adult	adultDD	83
Pest events (°C degree-days)		
Egg event – suggested label “beginning of egg hatch”	eggEventDD	75
Larva event – suggested label “mid-larval peak”	larvaeEventDD	107
Pupa event – suggested label “first adult emergence”	pupaeEventDD	138
Adult event – suggested label “first egg-laying”	adultEventDD	25
Chill stress		
Chill stress temperature threshold (°C)	chillstress_threshold	2
Chill degree-day (°C) limit when most individuals die	chillstress_units_max1	300
Chill degree-day (°C) limit when all individuals die	chillstress_units_max2	515
Heat stress		
Heat stress temperature threshold (°C)	heatstress_threshold	37
Heat stress degree-day (°C) limit when most individuals die	heatstress_units_max1	600
Heat stress degree-day (°C) limit when all individuals die	heatstress_units_max2	950
Cohorts		
Degree-days (°C) to emergence (average)	distro_mean	25
Degree-days (°C) to emergence (variation)	distro_var	200
Minimum degree-days (°C) to emergence	xdist1	1
Maximum degree-days (°C) to emergence	xdist2	60
Shape of the distribution	distro_shape	normal

Table 3. Parameter values used in the CLIMEX model for *Tuta absoluta*.

CLIMEX parameter	Code	Value
Temperature		
Lower temperature threshold (°C)	DV0	7
Lower optimal temperature (°C)	DV1	14
Upper optimal temperature (°C)	DV2	30
Upper temperature threshold (°C)	DV3	34.6
Degree-days per generation (°C days)	PDD	460
Moisture		
Lower soil moisture threshold	SM0	0.1
Lower optimal soil moisture	SM1	0.4
Upper optimal soil moisture	SM2	1.6
Upper soil moisture threshold	SM3	2
Cold stress		
Cold stress temperature threshold (°C)	TTCS	4
Cold stress temperature rate (week^{-1})	THCS	−0.001
Heat stress		
Heat stress temperature threshold (°C)	TTHS	34.6
Heat stress temperature rate (week^{-1})	THHS	0.0001
Dry stress		
Dry stress threshold	SMDS	0.1
Dry stress rate (week^{-1})	HDS	−0.01
Wet stress		
Wet stress threshold	SMWS	2
Wet stress rate (week^{-1})	HWS	0.015
Hot-wet stress		
Hot-wet temperature threshold (°C)	TTHW	30
Hot-wet moisture threshold	MTHW	0.6
Hot-wet stress rate (week^{-1})	PHW	0.003

Fig. 1. Predictions of climatic suitability for *Tuta absoluta* (TABS) in Eurasia and CONUS as estimated by the Ecoclimatic Index (EI) in CLIMEX. Cyan circles depict field population records for the species that were derived from the literature.

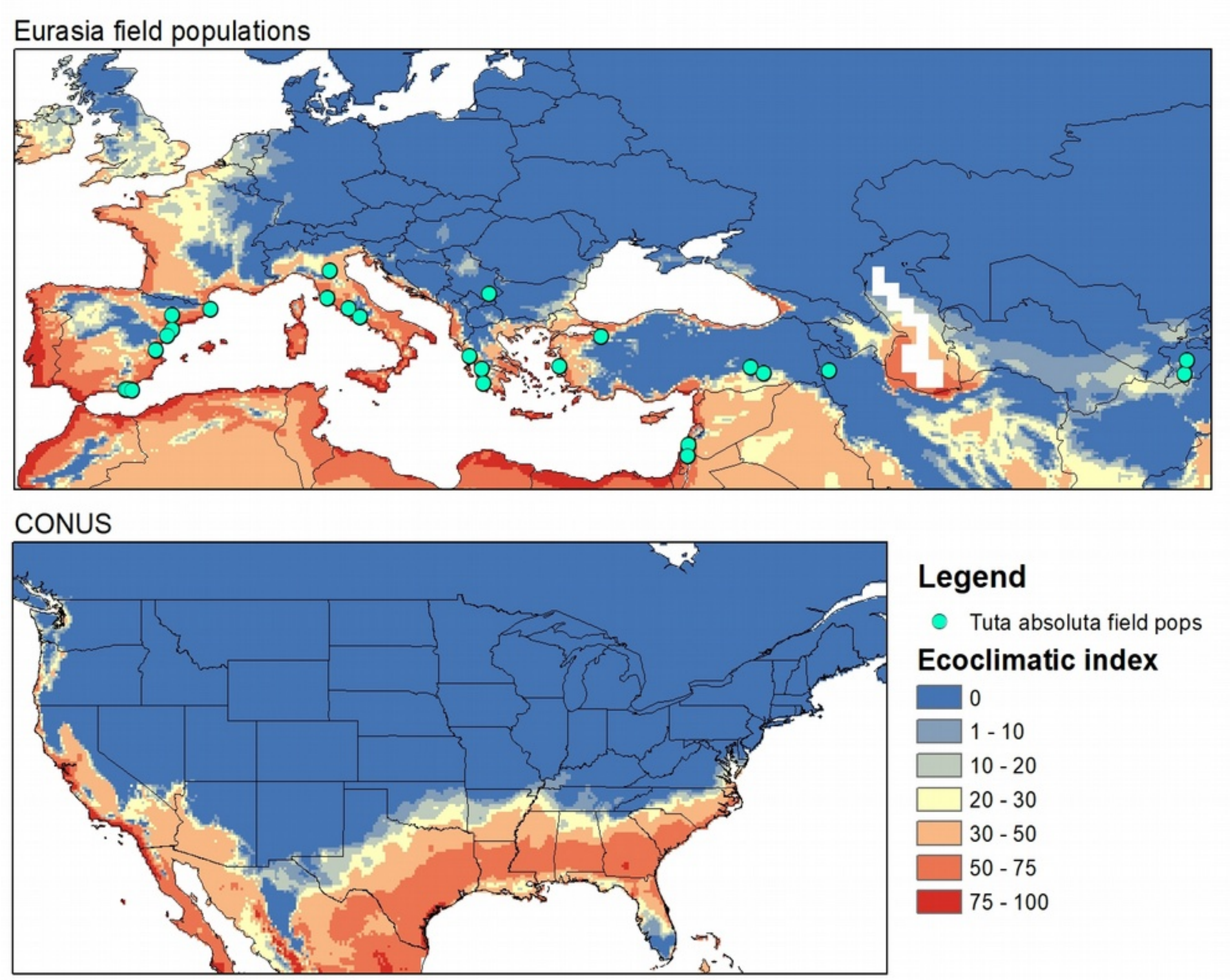


Fig. 2. Maps of cold/chill stress units for *Tuta absoluta* (TABS) produced by (a) CLIMEX (cold stress temperature threshold, TTCS = 4ºC) and (b) DDRP (chill stress temperature threshold = 2ºC). DDRP chill stress units have been scaled from 0 to 100 to match the scale used by CLIMEX. Reference climate 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 (300 and 515 CSUs, respectively; Table 2).

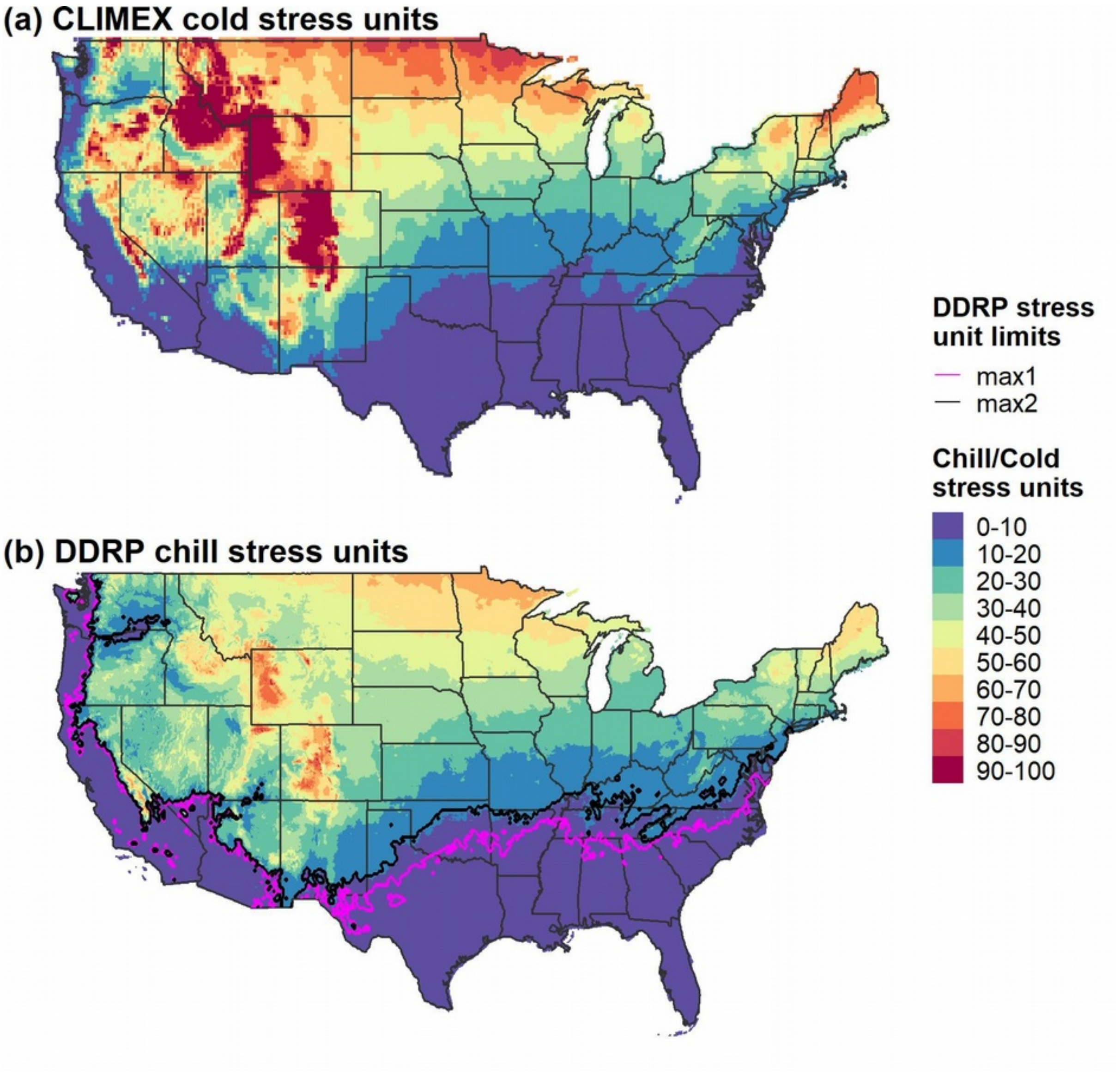


Fig. 3. Maps of heat stress units for *Tuta absoluta* (TABS) produced by (a) CLIMEX (heat stress temperature threshold, TTHS = 34.6ºC) and (b) DDRP (heat stress temperature threshold = 37ºC). DDRP heat stress units have been scaled from 0 to 100 to match the scale used by CLIMEX. Reference climate data 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 (600 and 950 CSUs, respectively; Table 2).

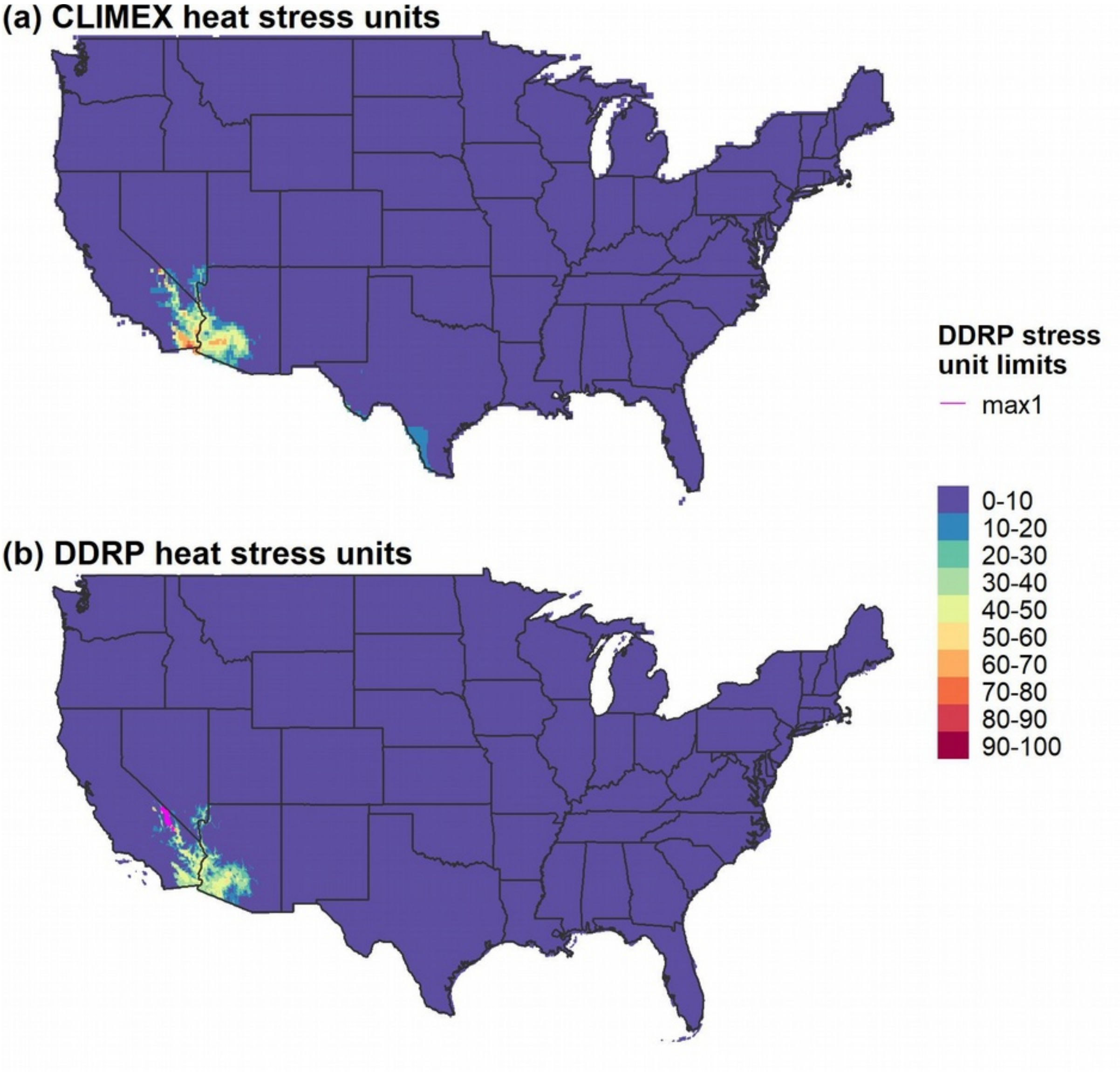
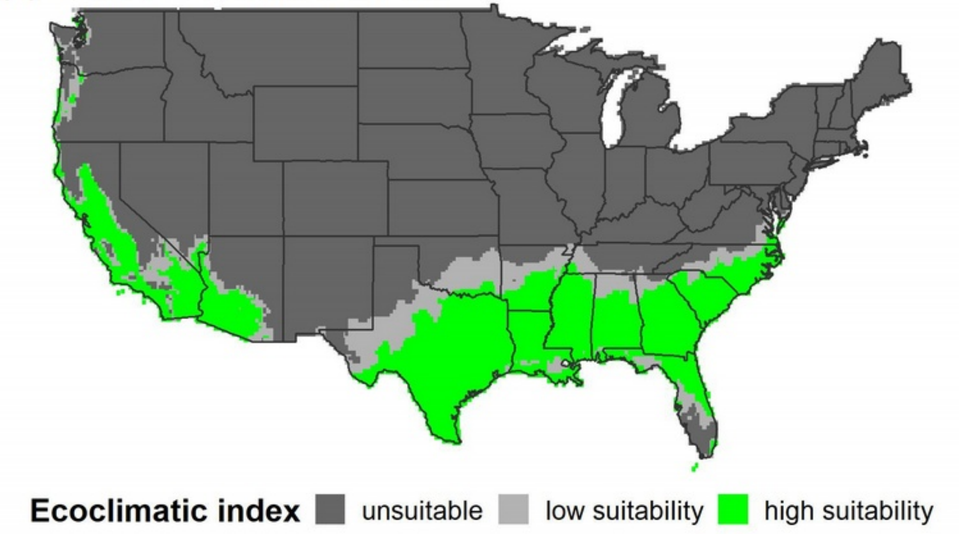


Fig. 4. Climate suitability models for *Tuta absoluta* (TABS) in CONUS produced by (a) CLIMEX and (b) DDRP. DDRP measures exclusion status of the species based on chill and heat stress units (all stress exclusion). CLIMEX applied a cold stress threshold of 4ºC while DDRP applied a chill stress threshold of 2ºC. Conversely, a heat stress threshold of 34.6 ºC vs. 37 ºC were applied in CLIMEX and DDRP, respectively. Reference climate data for DDRP were from 1960–1990 Normals (matched to available CLIMEX data).

(a) CLIMEX ecoclimatic index



(b) DDRP all stress exclusion

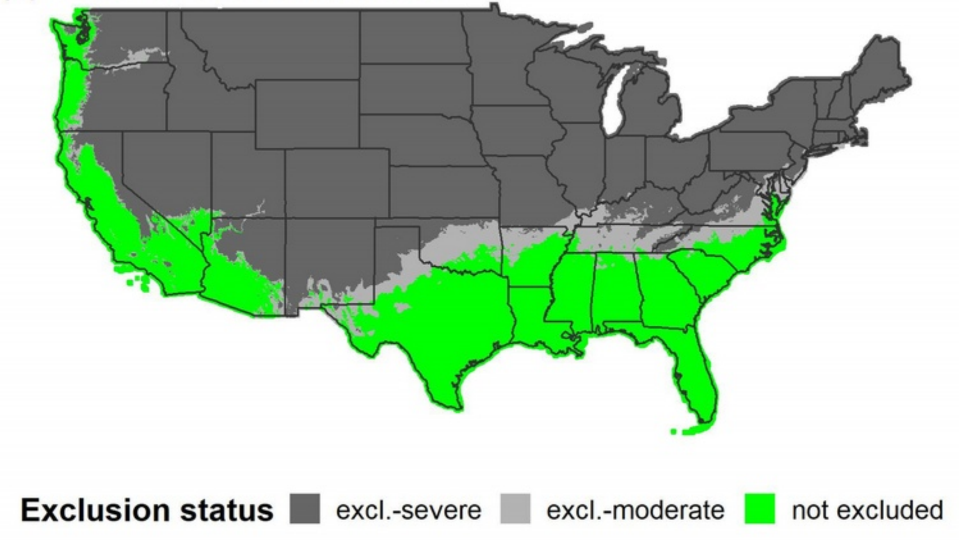


Fig. 5. Map of hot-wet stress units for *T. absoluta* produced by CLIMEX.

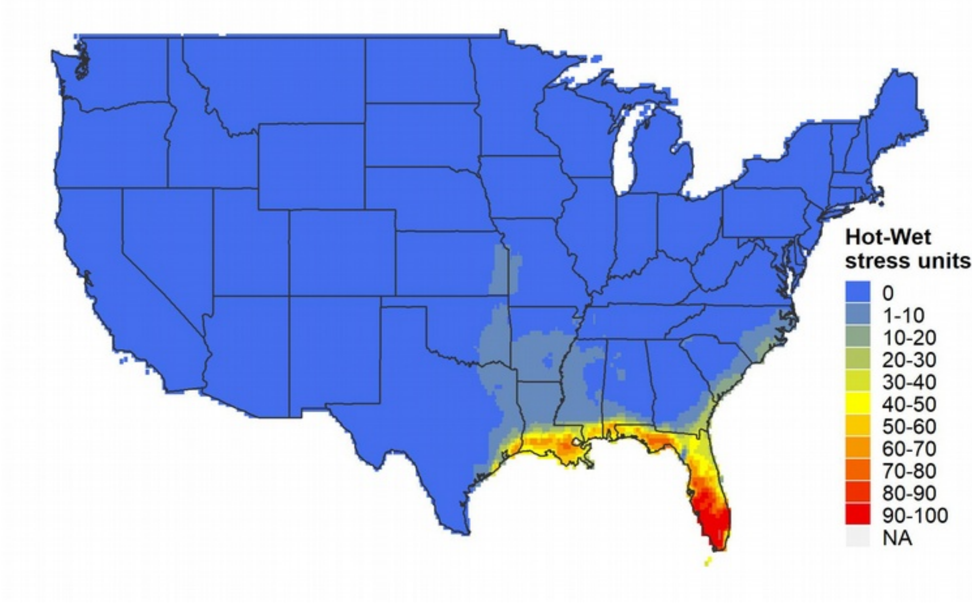


Fig. 6. Map depicting the date of first egg laying by first generation females with severe climate stress exclusion for *Tuta absoluta* (TABS) for 2012 (based on chill and heat stress units) produced by DDRP.

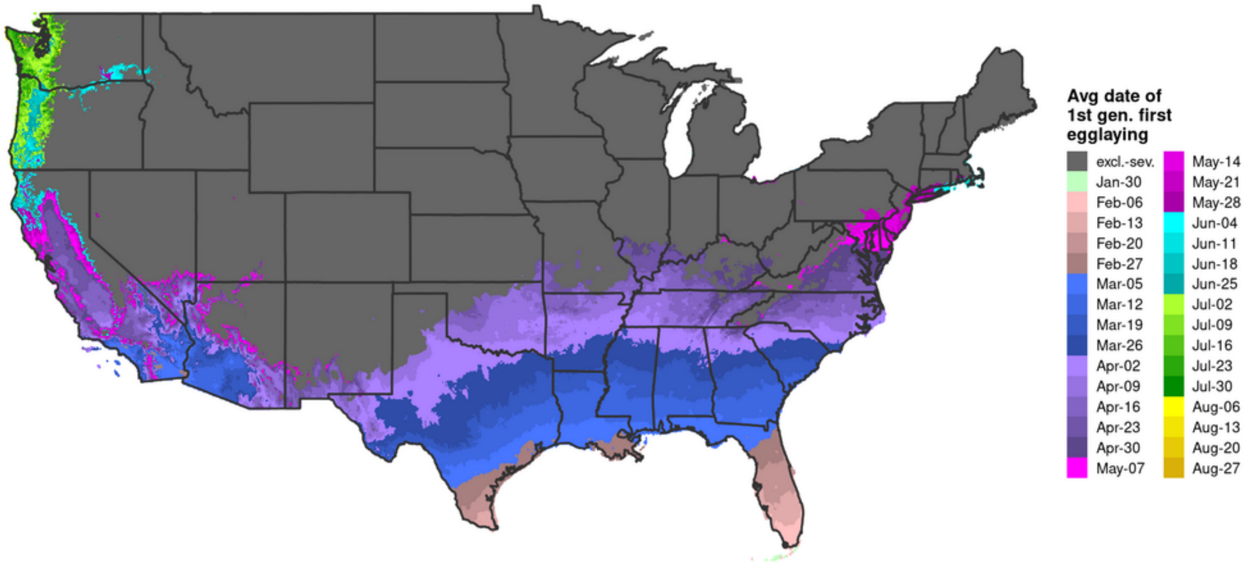


Fig. 7. Map showing the voltinism (number of generations) of *Tuta absoluta* (TABS) with severe climate stress exclusion (based on chill and heat stress units) for 2012 produced by DDRP.