Small Tomato Borer/Tomato Fruit Borer
***Neoleucinodes elegantalis* (Lepidoptera: Crambidae)**
Phenology/Degree-Day and Climate Suitability Model Analysis for USPEST.ORG
Prepared for USDA APHIS PPQ
Version 1.0. 3/13/2019

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Summary
A phenology model and temperature-based climate suitability model for the small tomato borer (STB)/tomato fruit borer, *Neoleucinodes elegantalis*, was developed using data from available literature and through modeling in CLIMEX (Sutherst et al. 2007) and DDRP (Degree-Days, Risk, and Pest event mapping; under development for uspest.org).

Introduction
Neoleucinodes elegantalis is a pest of several Solanaceaeus crops, including tomato, eggplant, and pepper. The species is a serious threat to tomato farmers owing to the great economic losses caused by direct damage to crop products by larvae. Currently, it is present in some countries of South, Central, and North America and in the Caribbean (Díaz-Montilla et al. 2013a; Bulletin OEPP, 2015). There have been at least 1175 records of interception from the United States.

Phenology modeling
Objective.—We aimed to estimate rates and degree days of development in *N. elegantalis* by solving for a best overall common threshold and corresponding developmental degree days (DD) 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 (Coop 2017). We re-interpreted temperature vs. development rate data from a lab development study of *N. elegantalis* on hybrid tomato (Paronset) at five temperatures (Moraes and Foerster 2015). 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. Moraes & Foerster (2015) suggested a low threshold of *ca.* 8.8°C for eggs, 7.7°C for larvae and pupae, and 17.5°C for pre-oviposition. In some cases, large threshold disparities across stages can create problems for simple DD models that require a common threshold. The range of thresholds derived from this study was deemed to be a relatively minor issue. Cooler temperatures were not tested, which lowers the accuracy of low thresholds for each stage. Additionally, for the linear portion of the temperature response relationship, only three temperatures were used for measuring pre-oviposition, and the data point for 20°C is not well aligned with the other two points. This result suggests that the estimated low threshold of 17.5°C may be too high. We solved for a common low threshold of 8.89°C using data from longer duration stages (larvae and pupae) instead of the shorter pre-oviposition stage. We also considered solving for a low threshold of 10.0 or 11.1°C as other plausible lower thresholds, but 8.89°C produced a better overall fit for egg-to-adult development. We used 30°C as the upper development threshold (with the horizontal cutoff method) because fertilization and embryonic development in Moraes & Foerster's (2015) experiment were arrested at this temperature. A summary of temperature developmental thresholds is reported in Table 1.

Development in degree days.—At a lower threshold of 8.89°C, egg, larval, pupal, egg-to-adult and pre-oviposition DD requirements were 86, 283, 203, 573, and 60 DDs, respectively. Moraes & Foerster's (2015) analyses of oviposition and adult longevity periods indicated that oviposition time following a 60 DDC pre-oviposition stage was only 51 DDC, which is rather short considering that female longevity is much longer (190 DDC). We used 80% of this oviposition time (41 DDC) for peak generation time, and 60% of female longevity for the end of oviposition (*ca.* 90%; 142DDC).

From Source #2 (Moraes & Foerster 2014), who reared *N. elegantalis* on three tomato cultivars at one temperature (20°C), average development time was 82 DDC for eggs and 582 DDC for egg-to-adult compared to 86 and 573 DDC from Moraes & Foerster (2015). These results compare favorably.

From Source #3 (Marcano 1991), who reared *N. elegantalis* on tomato at 3-4 temperatures, average development time was 79 DDC for eggs and 525 DDC for egg-to-adult. The egg-to-adult time was *ca*. 48 DDC shorter than for Moraes & Foerster (2015), but remains within a reasonable range.

The resulting summary for degree-day requirements is reported in Table 2. We used the assumption that there is no apparent delay in spring egg-laying, meaning that the normal pre-oviposition period transpires before first spring egg-laying. The model is generated for first and peak oviposition times for the overwintering adult generation and each subsequent generation.

Comparison of CLIMEX and DDRP models

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 units; Table 1) resulted in map outputs most similar to CLIMEX models that applied the "best-fit" parameters proposed by a recent CLIMEX modeling study of *N. elegantalis* (da Silva et al. 2018). For these analyses, we ran DDRP and CLIMEX models after changing only a single parameter at a time. 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 Table 1.

Background.—The CLIMEX model presented by da Silva et al. (2018) includes both temperature and soil moisture stress factors, whereas DDRP includes only temperature stress factors because gridded (DDRP-relevant resolution at 4K) soil moisture monitoring and prediction data are unavailable. While the absence of soil moisture data in DDRP is a limitation, temperature is the main abiotic factor controlling the distribution and establishment of *N. elegantalis* (EPPO, 2014; da Silva et al. 2018). The authors arrived at their best-fit parameters by choosing the set that most accurately predicted areas of suitability in regions of South America where the species is known to occur.

Chill stress parameters.—In their CLIMEX model, da Silva et al. (2018) applied a cold stress degree-day threshold (DTCS) of 15 and a cold stress accumulation rate in degree days (DHCS) of -0.001. Using the DDRP system of chill stress, which accumulates chill units using daily temperatures lower than an upper threshold, we derived a chill stress temperature threshold of -1ºC (Fig. 1), a value much lower than the related CLIMEX parameter. The disparity in values may be due to differences in how each model defines cold/chill stress: CLIMEX assumes that animals die from starvation because temperatures are too low to maintain metabolism, whereas DDRP's chill stress is assumed to cause death more directly than by starvation. We chose to use a chill stress temperature threshold of -1ºC for DDRP for three reasons. First, the USDA has proposed that *N. elegantalis* may be able to establish in the United States within Plant Hardiness Zones 7–11 due to its ability to survive in both warm and cold climates and its distribution throughout South and Central America, which includes elevations as high as *ca.* 2800 m (Díaz-Montilla et al. 2011; Díaz-Montilla et al. 2013a; Díaz-Montilla et al. 2017). Second, Díaz-Montilla et al. (2013b) found distinctive genetic lineages of *N. elegantalis* across climatically diverse localities spanning 0 to 2600 m above sea level in Colombia, which supports the possibility of a cold-adapted lineage establishing in relatively cooler areas of the US. Finally, we found that a CLIMEX model with a cold stress temperature threshold (TTCS) of -1ºC produced an ecoclimatic index map and chill stress unit map that aligned closely with DDRP climate stress exclusion and chill stress maps (Figs 1 and 2). We tested different values of TTCS because this parameter is more directly comparable to the DDRP chill stress temperature threshold parameter (we note however that adjusting the DTCS parameter produced nearly identical results; results not shown). The cold stress accumulation rate was kept at -0.0001 wk^{-1}.

Heat stress parameters.—Da Silva et al. (2018) found that the heat stress temperature threshold (TTHS) had the greatest impact in changing the size of unsuitable and low-suitability areas of *N. elegantalis* in South America. They set TTHS to 30°C, a value supported by the study of Moraes & Foerster (2015), which found that adults died after a week at 30°C and eggs were infertile. We found that a DDRP model that applied a heat stress temperature threshold of 35°C produced heat stress unit maps that most closely aligned with those of CLIMEX (Fig. 3). CLIMEX and DDRP models both predicted significant heat stress unit accumulation in southern parts of California, Arizona, and Texas. The CLIMEX ecoclimatic index map predicted unsuitable conditions in these areas, and the DDRP climate stress exclusion maps predicted exclusion of the species there as well. Decreasing the heat stress temperature threshold to 33°C in DDRP resulted in excluding the species from areas in eastern Texas and western Louisiana, a region predicted to be highly suitable by da Silva et al.'s (2018) CLIMEX model.

The lack of soil moisture data in the DDRP model could explain why it predicted suitability in certain parts of western Texas and Arizona where CLIMEX predicted unsuitable conditions (Fig. 1). Data concerning the impacts of hot-dry stress on *N. elegantalis* are unavailable; however, the absence of this species in hot and dry climate zones in South America suggests that it does not persist in hot, desert environments such as those found in the American Southwest. On the other hand, it does occur in dry regions of Argentina with a mean monthly rainfall of 608 mm, which is similar to the annual rainfall of Mediterranean climates in the US.

Suggested applications

The DDRP model may be run to test where *N. elegantalis* may become established and reproduce in the continental US under past, current and future weather 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. 4), and (b) potential voltinism (number of generations; Fig 5).

Improvements needed

The largest error for many phenology models is in the initial conditions: how does one manage the overwintering stage(s) and how do they respond to the wide range of warming conditions possibly encountered for a large region such as the continental US? This model currently assumes that moths have only a nominal 60 DDC before egg-laying behaviors may occur. This may actually not reflect behavior in the sub-tropical zones of the US, where flight and reproduction could occur even earlier. It is perhaps more likely, however, at least in the more temperate zones, that a much longer spring warm-up is needed – possibly reflecting the transplanting of commercial tomato, which would occur much later. For example, tomatoes are generally not transplanted into bare soil until May or June in W. Oregon, which would be more like 300DDC vs 60 DDC. Reports of the beginning of flight in Central or South America are not available; however, this event is expected when early fruit develops on tomato plants.

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Tables and Figures

Table 1. *Neoleucinodes elegantalis* (STB) parameters resulting from phenological, CLIMEX, and DDRP modeling.

Parameter abbr.	Description	Units	Value	Model
eggLDT	egg lower developmental threshold	°C	8.89	DDRP
eggUDT	egg upper developmental threshold	°C	30	DDRP
larvaeLDT	larvae lower developmental threshold	°C	8.89	DDRP
larvaeUDT	larvae upper developmental threshold	°C	30	DDRP
pupaeLDT	pupaee lower developmental threshold	°C	8.89	DDRP
pupaeUDT	pupae upper developmental threshold	°C	30	DDRP
adultLDT	adult lower develpmental threshold	°C	8.89	DDRP
adultUDT	adult upper developmental threshold	°C	30	DDRP
eggDD	egg DD	DDC	86	DDRP
larvaeDD	larvae DD	DDC	283	DDRP
pupaeDD	pupae DD	DDC	203	DDRP
adultDD	adult DD	DDC	101	DDRP
OWadultDD	overwintering adult DD	DDC	86	DDRP
eggEventDD	DDs until beginning of egg hatch	DDC	80	DDRP
larvaeEventDD	DDs until mid-larval development	DDC	140	DDRP
pupaeEventDD	DDs until mid-pupal development	DDC	100	DDRP
adultEventDD	DDs until first egglaying by females	DDC	60	DDRP
chillstress_threshold	chill stress threshold	°C	-1	DDRP
chillstress_units_max1	chill DD limit when most individuals die	DDC	150	DDRP
chillstress_units_max2	chill DD limit when all individuals die	DDC	300	DDRP
heatstress_threshold	heat stress threshold	°C	35	DDRP
heatstress_units_max1	heat stress DD limit when most individuals die	DDC	50	DDRP
heatstress_units_max2	heat stress DD limit when all individuals die	DDC	140	DDRP
SM0	lower soil moisture threshold	-	0.35	CLIMEX
SM1	lower optimal soil moisture	-	0.7	CLIMEX
SM2	upper optimal soil moisture	-	1.5	CLIMEX
SM3	upper soil moisture threshold	-	2.5	CLIMEX
DV0	lower temperature threshold	°C	8.8	CLIMEX
DV1	lower optimal temperature	°C	15	CLIMEX
DV2	upper optimal temperature	°C	27	CLIMEX
DV3	upper temperature threshold	°C	30	CLIMEX
TTCS	threshold temp above which cold stress accum.	°C	-1	CLIMEX
THCS	cold stress rate	wk^{-1}	-0.001	CLIMEX
TTHS	threshold temp above which heat stress accum.	°C	30	CLIMEX
THHS	heat stress rate	wk^{-1}	0.0007	CLIMEX
SMDS	dry stress threshold	-	0.35	CLIMEX

Table 1 cont.

Parameter abbr.	Description	Units	Value	Model
HDS	dry stress rate	wk^{-1}	-0.001	CLIMEX
SMWS	wet stress threshold	-	2.5	CLIMEX
HWS	wet stress rate	wk^{-1}	0.002	CLIMEX
DVCS	developmental temperature threshold	°C	8.8	CLIMEX
DVHS	DD accumulation above DV0	DDC	30	CLIMEX
DV4	degree accumulation above DVCS	DDC	100	CLIMEX
MTS	DD accumulation above DVHS	DDC	7	CLIMEX
PDD	DDs per generation	DDC	588.2	CLIMEX

Table 2. *Neoleucinodes elegantalis* (STB) degree-day model summary based primarily on Moraes and Foerster (2015).

	Deg.s (C)	Deg.s (F)
Lower Threshold:	8.89	48
Upper Threshold:	32.22	90
Calculation Method:	Single Sine	
Model Start:	January 1st	

Degree-Day Requirements	DDs (C)	DDs (F)
Egg	86	156
Larvae+pupae	486	875
Egg-to-Adult	573	1031
Pre-OV	60	108
DDds to Peak OV	101	181
DDs to 90% OV	174	313
Egg-to-1st-OV (min gen. time)	633	1139
Egg-to-Peak-OV (avg gen. time)	674	1212

Events Summary	DDs (C)	DDs (F)
First Spring Egg-Laying	60	108
Peak Spring Egg-Laying	101	181
First adults G1	633	1139
Peak 1st Gen. Egg-Laying	774	1394
Peak 2nd Gen. Egg-Laying	1448	2606
Peak 3rd Gen. Egg-Laying	2121	3819
Peak 4th Gen. Egg-Laying	2795	5031
Peak 5th Gen. Egg-Laying	3468	6243
etc…		

Fig. 1. *Neoleucinodes elegantalis* (STB) Map of (a) ecoclimatic index produced by CLIMEX and (b) exclusion status based on chill and heat stress units produced by DDRP. Both the CLIMEX and DDRP model applied a cold/chill stress temperature threshold of -1ºC. Reference climate data for DDRP were from 1960-1990 Normals (matched to available CLIMEX data). The CLIMEX model applied a heat stress temperature threshold of 30ºC, whereas the DDRP model applied a heat stress temperature threshold of 35ºC.

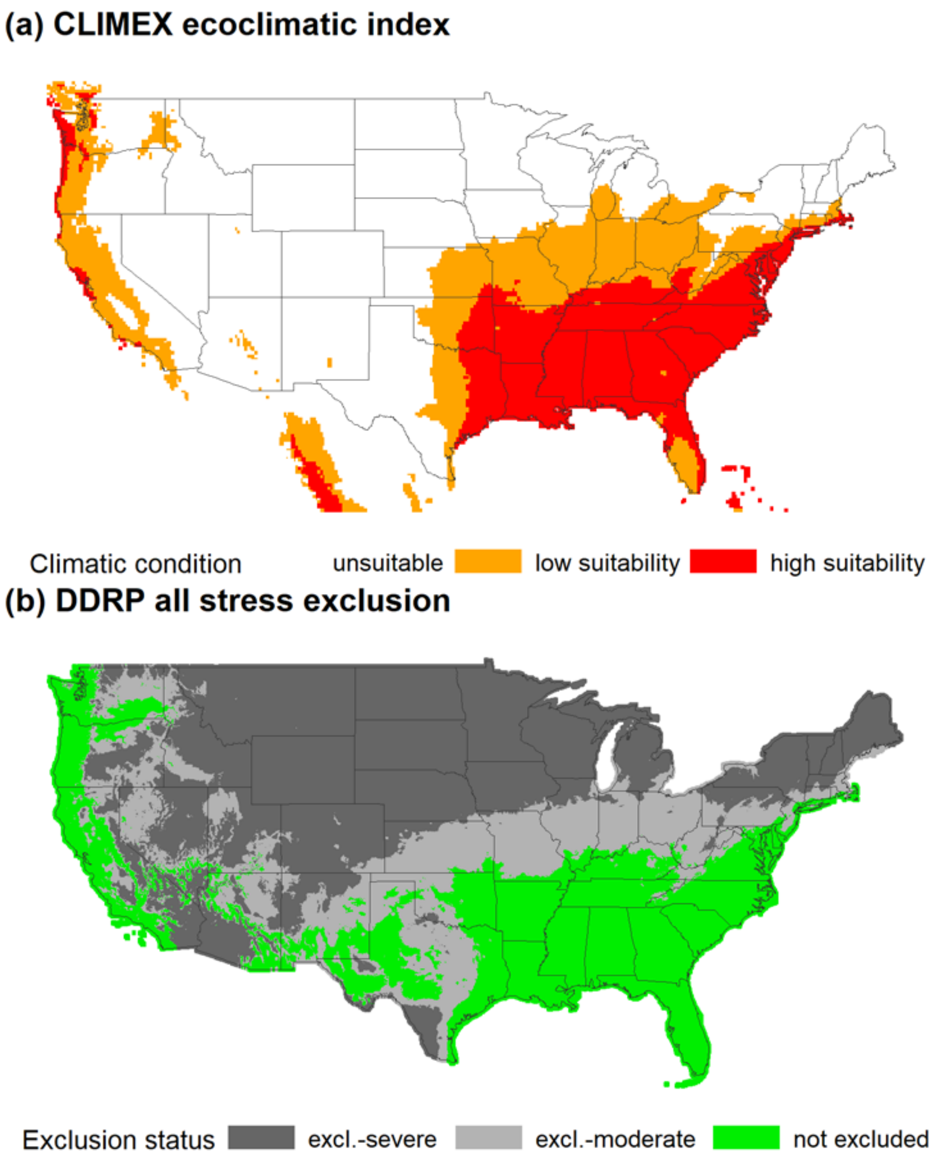

Fig. 2. *Neoleucinodes elegantalis* (STB) maps of cold/chill stress units produced by CLIMEX (cold stress temperature threshold, TTCS = -1ºC) and DDRP (chill stress temperature threshold = -1ºC). DDRP chill stress units have been scaled from 0 to 100 to match the scale used by CLIMEX. Reference climate 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 (150 and 300 CSUs, respectively; Table 1).

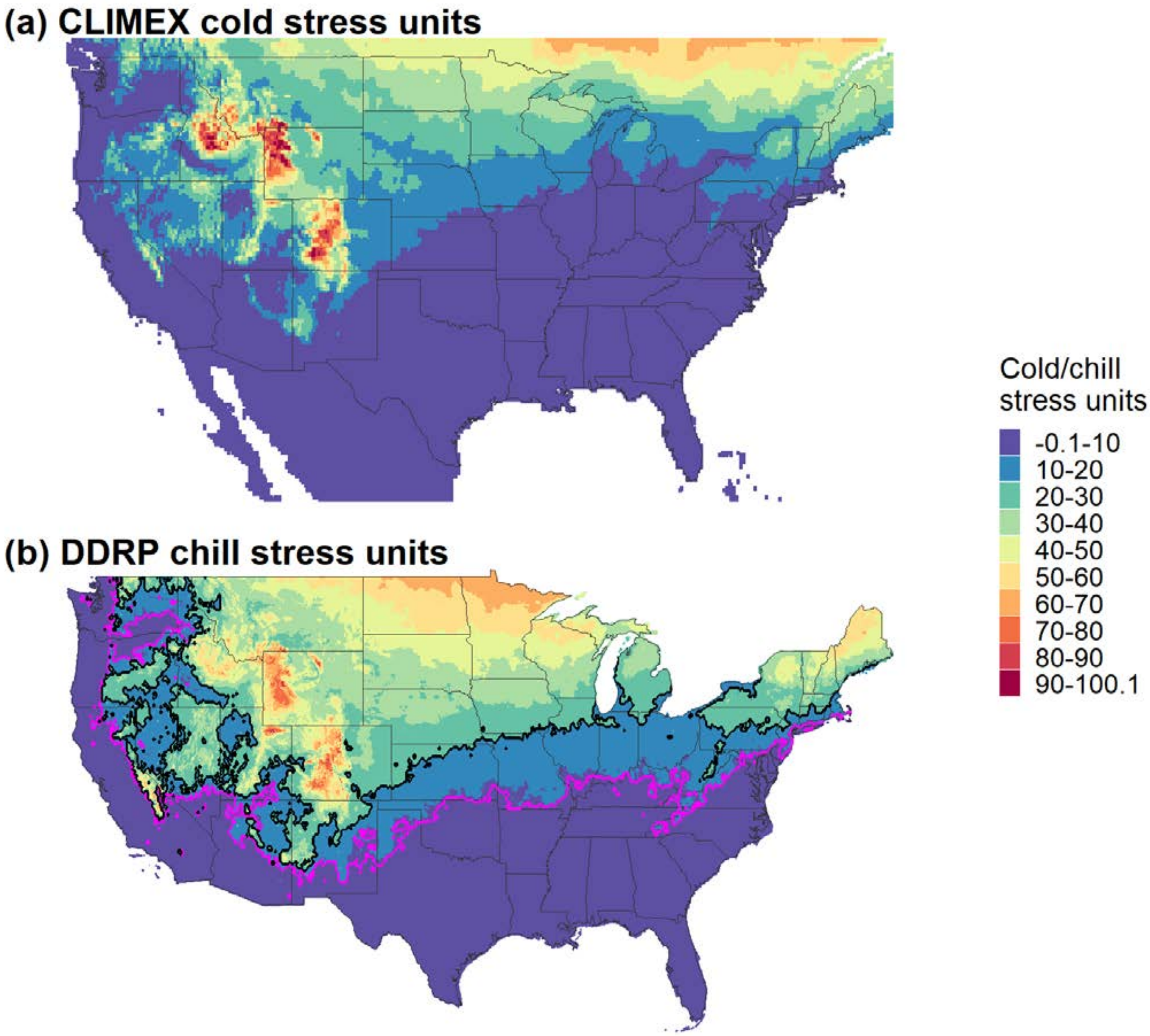

Fig. 3. *Neoleucinodes elegantalis* (STB) maps of heat stress units produced by (a) CLIMEX (heat stress temperature threshold, THCS = 30ºC) and (b) DDRP (heat stress temperature threshold = 35ºC. DDRP heat stress units have been scaled from 0 to 100 to match the scale used by CLIMEX. Reference climate 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 (50 and 140 HSUs, respectively; Table 1).

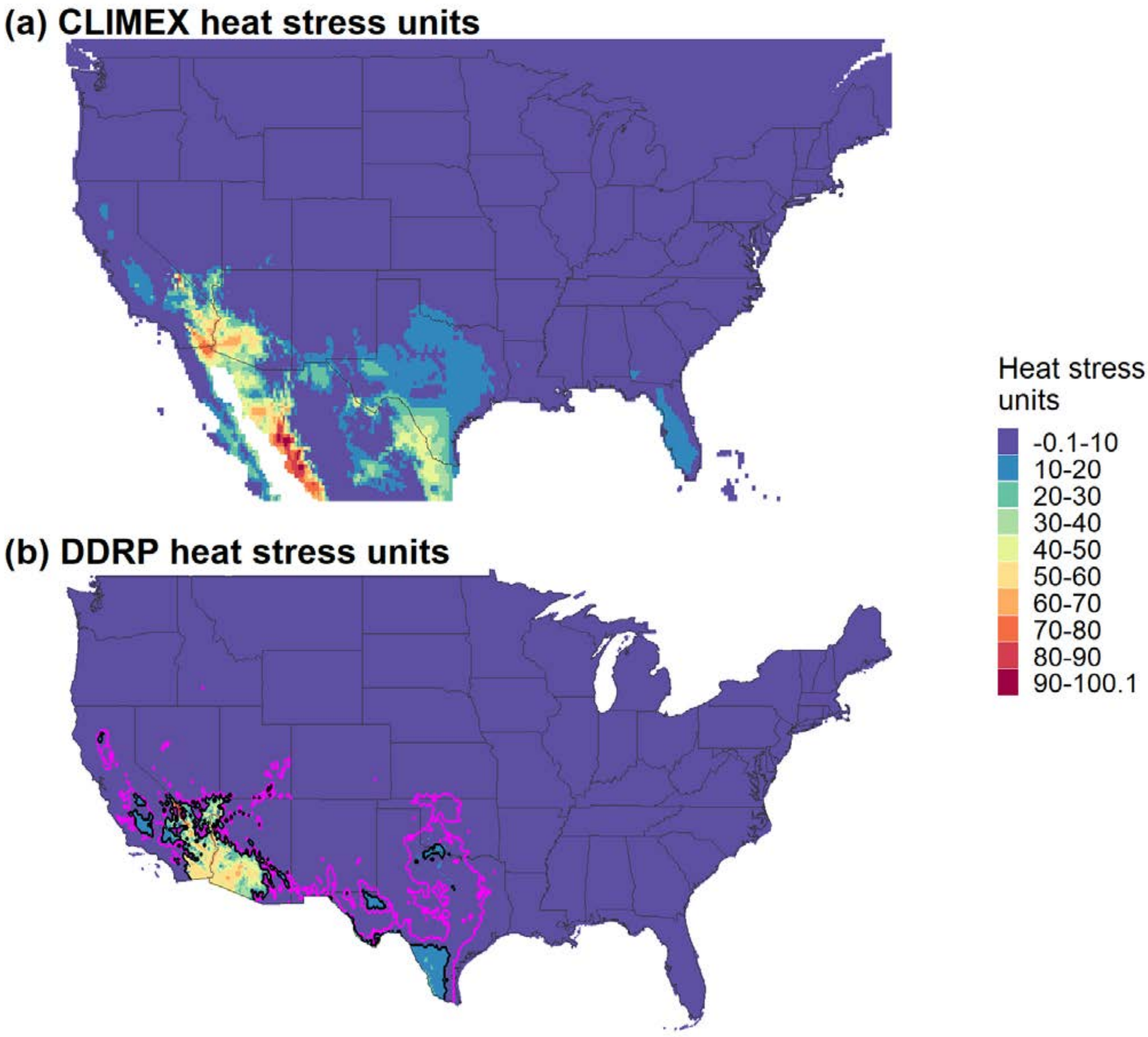

Fig. 4. *Neoleucinodes elegantalis* (STB) map of voltinism (number of generations) with severe climate stress exclusion for 2012 (based on chill and heat stress units) produced by DDRP.

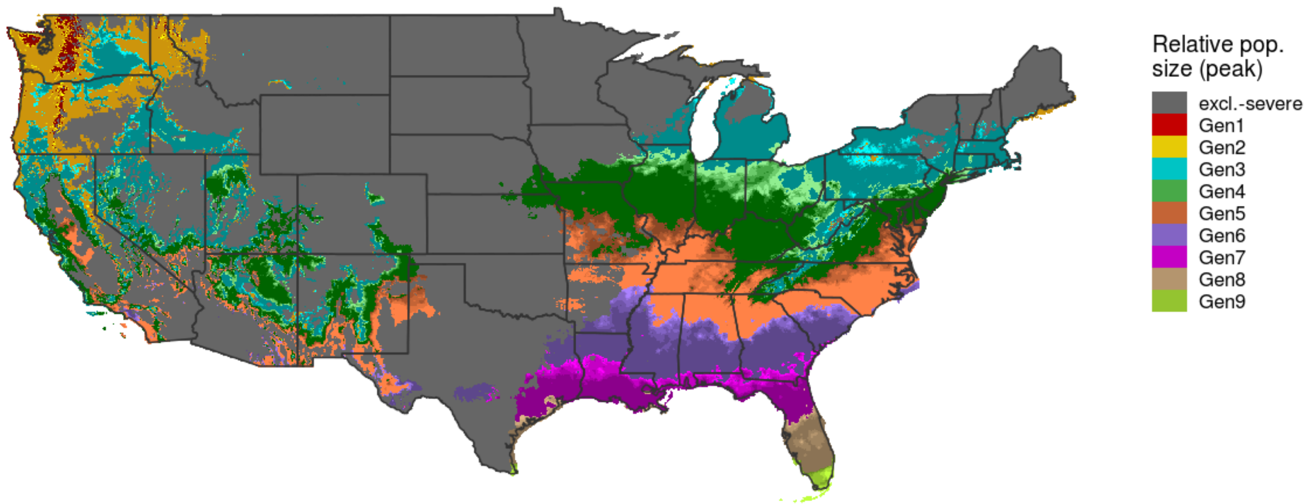

Fig. 5. *Neoleucinodes elegantalis* (STB) map of the date of first egg laying by females of the overwintering generation with severe climate stress exclusion for 2012 (based on chill and heat stress units) produced by DDRP.