Small Tomato Borer/Tomato Fruit Borer

***Neoleucinodes elegantalis* (Lepidoptera: Crambidae)**

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 small tomato borer (STB)/tomato fruit borer, *Neoleucinodes elegantalis*, was developed using data from available literature and through modeling in CLIMEX (Kriticos et al. 2015) and DDRP (Degree-Days, Risk, and Pest event mapping; under development for uspest.org).

Introduction

Neoleucinodes elegantalis is a pest of several Solanaceous 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. 2013; Bulletin OEPP, 2015). There have been at least 1175 records of interception from the United States.

Phenology model

Objective.—We estimated 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 at http://uspest.org/wea/Neoleucinodes_elegantalis_STB_model.pdf (Coop 2019). 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 and 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 and Foerster's (2015) experiment were arrested at this temperature. A summary of temperature developmental thresholds is reported in Tables 1 and 2.

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 and 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 and 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 and 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 and 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. We applied seven cohorts to approximate a normal distribution of OW adult emergence times that spanned 0 to 111 DDC (average = 50 DDC). This range assumes that over-wintered adults would begin finding hosts and feeding during the pre-oviposition period prior to first egg-laying.

Climate suitability model

Objective.—Our objective was to estimate which climate stress parameters in DDRP (cold stress temperature threshold, heat stress threshold, and cold and heat stress units; Table 2) 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* (Table 2; da Silva et al. 2018). DDRP models used a PRISM data set of daily temperature data from 1961 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.

CLIMEX model.—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. 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.

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. We substituted this parameter with the cold stress temperature threshold (TTCS) and used a less stringent threshold value of 2°C. The lowest monthly temperatures experienced at high-elevation areas where the species occurs in Colombia (Bogota, elevation = ca. 2600 m) (Díaz et al. 2011) and in Ecuador (El Chaco, elevation = 1600 m) (Noboa et al. 2017) have reached 2°C according to records collected since 2017 (https://rp5.ru/ and https://www.worldweatheronline.com, respectively). 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 and Foerster (2015), which found that adults died after a week at 30°C and eggs were infertile.

DDRP model.—We applied a cold and heat stress temperature threshold of 2ºC and 32ºC in DDRP, respectively. Both of these thresholds resulted in a cold and heat stress map that aligned well with the equivalent maps produced by CLIMEX (Fig. 1). We adjusted the moderate and severe temperature stress limits to generally correspond with the results of the ecoclimatic index (EI) maps produced by CLIMEX. Specifically, DDRP predicted severe stress exclusion in areas where CLIMEX predicted unsuitable conditions (EI = 0), whereas moderate stress exclusion was predicted in areas where CLIMEX predicted low suitability (0 < EI < 10; Fig. 2). Both programs predicted that cold stress was the major factor that limited the distribution of the species in CONUS. However, significant heat stress unit accumulation in southern parts of California, Arizona, and Texas shaped the distribution as well.

Suggested applications

The DDRP model may be run to test where *N. elegantalis* may become established and reproduce in CONUS 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 average date of first generation beginning of egg hatch with severe climate stress exclusions (Fig. 3), and (b) potential voltinism (number of generations; Fig 4).

Improvements needed

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. 2). 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 CONUS.

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 56 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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Table 1. *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	56	100
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	56	100
Peak Spring Egg-Laying	111	200
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

Table 2. DDRP parameter values for *Neoleucinodes elegantalis*.

Parameter	Code	Value
Lower developmental thresholds (°C)		
Egg	eggLDT	8.89
Larvae	larvaeLDT	8.89
Pupae	pupaeLDT	8.89
Adult	adultLDT	8.89
Upper developmental thresholds (°C)		
Egg	eggUDT	30.0
Larvae	larvaeUDT	30.0
Pupae	pupaeUDT	30.0
Adult	adultUDT	30.0
Stage durations (°C degree-days)		
Egg	eggDD	86
Larvae	larvaeDD	283
Pupae	pupDD	203
Adult	adultDD	101
Pest events (°C degree-days)		
Egg event (beginning of egg hatch)	eggEventDD	80
Larva event (end of adult emergence)	larvaeEventDD	140
Pupa event (mid-pupal development)	pupaeEventDD	100
Adult event (first egg laying by females)	adultEventDD	60
Cold stress		
Cold stress temperature threshold (°C)	coldstress_threshold	2
Cold degree-day (°C) limit when most individuals die	coldstress_units_max1	550
Cold degree-day (°C) limit when all individuals die	coldstress_units_max2	900
Heat stress		
Heat stress temperature threshold (°C)	heatstress_threshold	32
Heat stress degree-day (°C) limit when most individuals die	heatstress_units_max1	180
Heat stress degree-day (°C) limit when all individuals die	heatstress_units_max2	340
Cohorts		
Avg. degree-days (°C) to OW adult emergence	distro_mean	50
Var. in degree-days (°C) to OW adult emergence	distro_var	1500
Minimum degree-days (°C) to OW adult emergence	xdist1	0
Maximum degree-days (°C) to OW adult emergence	xdist2	111
Shape of the distribution of degree-days (°C) to emergence	distro_shape	normal

Table 3. Parameter values used in the CLIMEX model for *Neoleucinodes elegantalis*.

CLIMEX parameter	Code	Value
Temperature		
Lower temperature threshold (°C)	DV0	8.8
Lower optimal temperature (°C)	DV1	15
Upper optimal temperature (°C)	DV2	27
Upper temperature threshold (°C)	DV3	30
Degree-days per generation (°C days)	PDD	588.2
Moisture		
Lower soil moisture threshold	SM0	0.35
Lower optimal soil moisture	SM1	0.7
Upper optimal soil moisture	SM2	1.5
Upper soil moisture threshold	SM3	2.5
Cold stress		
Cold stress temperature threshold (°C)	TTCS	2
Cold stress temperature rate ($week^{-1}$)	THCS	−0.001
Heat stress		
Heat stress temperature threshold (°C)	TTHS	30
Heat stress temperature rate ($week^{-1}$)	THHS	0.0007
Dry stress		
Dry stress threshold	SMDS	0.35
Dry stress rate ($week^{-1}$)	HDS	−0.001
Wet stress		
Wet stress threshold	SMWS	2.5
Wet stress rate ($week^{-1}$)	HWS	0.002

Fig. 1. Maps of (a) cold stress units and (b) heat stress units for *Neoleucinodes elegantalis* (STB) produced by DDRP and CLIMEX. Reference climate data for DDRP were from 1961–1990 Normals (matched to available CLIMEX data). The pink and black lines in DDRP maps depict the moderate and severe stress limits (max1 and max2, respectively; Table 1).

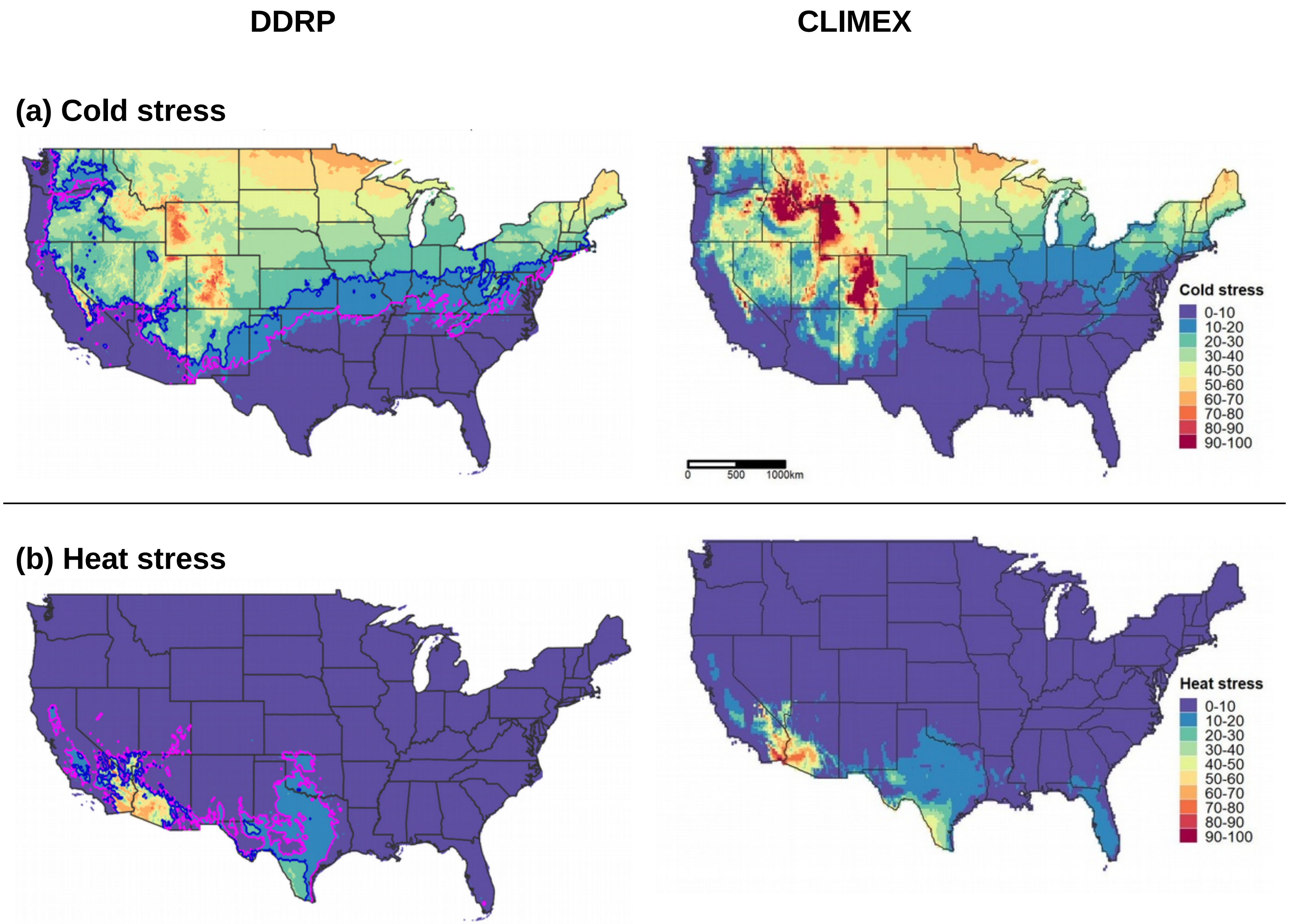
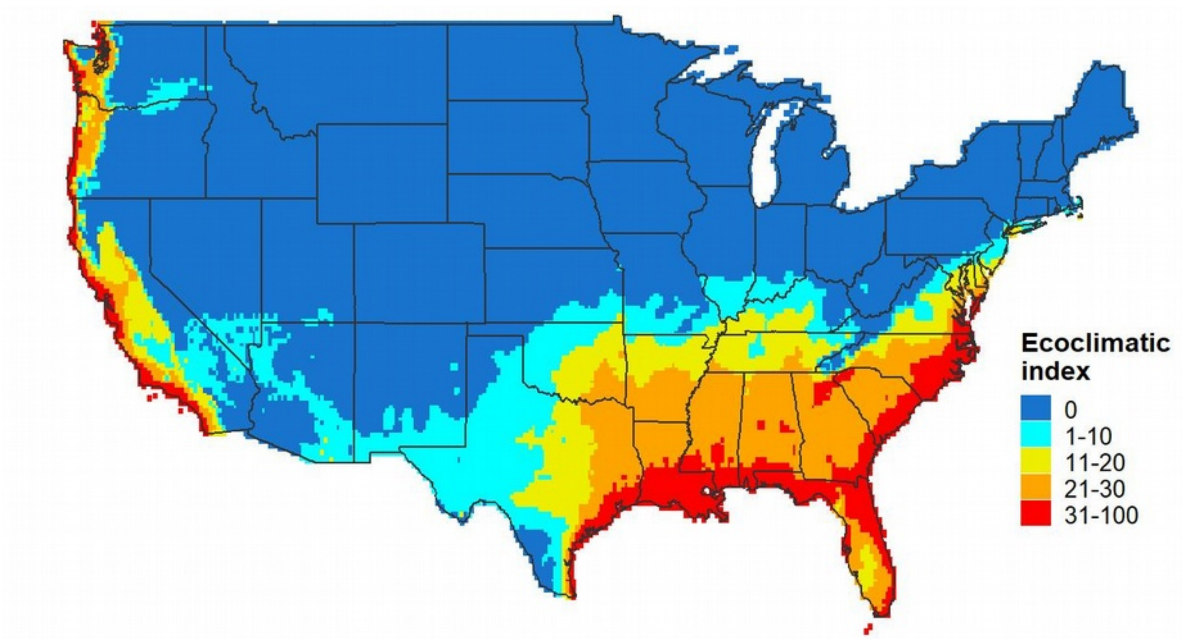


Fig. 2. Predictions of climate suitability for *Neoleucinodes elegantalis* (STB) produced by (a) CLIMEX and (b) DDRP. Reference climate data for DDRP were from 1961–1990 Normals (matched to available CLIMEX data). Both models applied a cold stress temperature threshold of 2ºC. The CLIMEX model applied a heat stress temperature threshold of 30ºC, whereas the DDRP model applied a heat stress temperature threshold of 32ºC.

(a) CLIMEX ecoclimatic index



(b) DDRP all stress exclusion

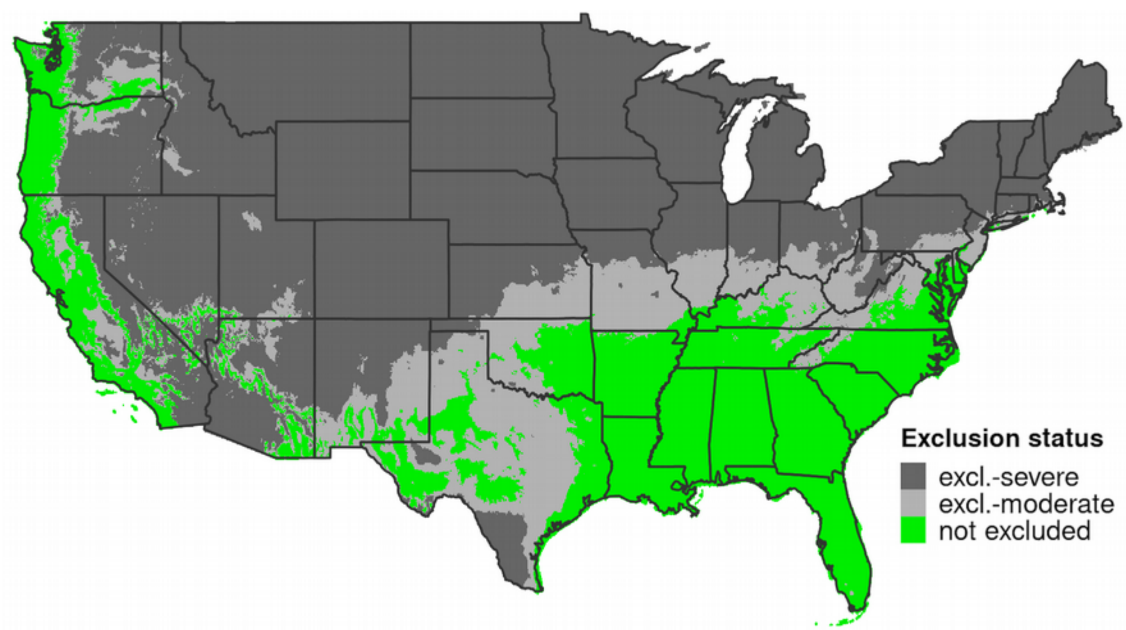


Fig. 3. Map of the average date of first generation beginning of egg hatch with severe climate stress exclusion (based on cold and heat stress units) for *Neoleucinodes elegantalis* (STB) for 2012 produced by DDRP.

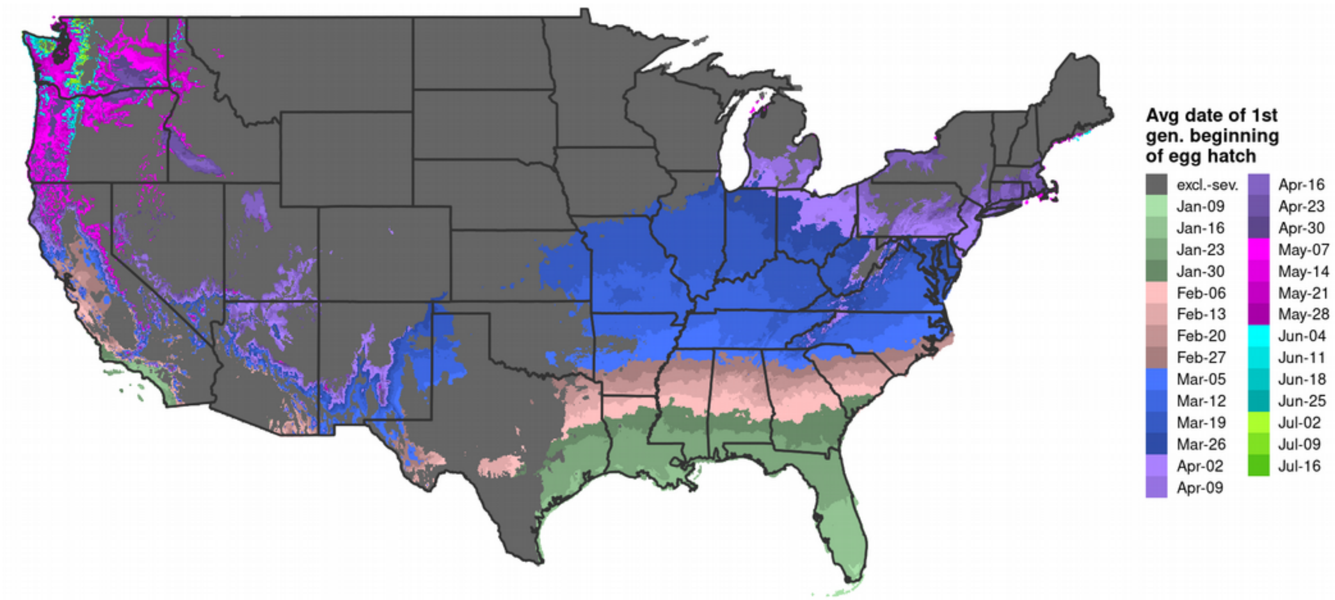


Fig. 4. Map of voltinism (number of generations) with severe climate stress exclusion (based on cold and heat stress units) for *Neoleucinodes elegantalis* (STB) for 2012 produced by DDRP.