Silver Y Moth
Autographa gamma (Lepidoptera: Noctuidae)
Phenology/Degree-Day and Climate Suitability Model White Paper for USPEST.ORG
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Summary

A phenology model and temperature-based climate suitability model for the silver Y moth (SLYM), *Autographa gamma* (Linnaeus), was developed using data from available literature and through modeling in CLIMEX v. 4 (Hearne Scientific Software, Melbourne, Australia; Kriticos et al. 2016) and DDRP (Degree-Days, Risk, and Pest event mapping; under development for uspest.org; Barker et al. 2020).

Introduction

Autographa gamma is a highly polyphagous pest found on cereals, fiber crops, *Brassica* spp., and other vegetables including legumes, tomato, potato, and tobacco (Venette et al. 2003, Sullivan and Molet 2014). The highly mobile species is widely distributed in the Palearctic region, where it is considered a pest in agricultural settings. Annual migrations involve wind-mediated dispersal of moths from southern overwintering grounds (southern and central Europe, North Africa and the Middle East) to northern zones of Eurasia to reproduce during the spring and summer (Hill and Gatehouse 1993, Honěk et al. 2002, Saulich et al. 2017, Torniainen and Mikonranta 2018). *Autographa gamma* has been intercepted hundreds of times at U.S. ports of entry on imported vegetables, cut flowers, ornamentals and other plants. It has a high likelihood of establishing if introduced to the U.S., and the consequences of its establishment are considered to be severe (Sullivan and Molet 2014).

Phenology model

Objective.—We estimated rates and degree days of development in *A. gamma* 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.

Developmental parameters—This is a summary of the spreadsheet analysis for *A. gamma* that is available online at http://uspest.org/wea/Autographa_gamma_model.pdf (Coop and Barker

2020). A summary of phenology model parameters is reported in Table 1. We solved for a common lower threshold of 8.89°C for immature stages (eggs, larvae, pupae) and female adults (pre-oviposition and longevity) by using the x-intercept method to analyze laboratory-based development data presented by Dochkova (1972; larvae and pupae), Harakly (1975; all stages), Duthie (1983; all stages), Hill and Gatehouse (1992; larvae, pupae, adults), Honěk et al. (2002; larvae only), and Taha et al. (2012; all stages). We calculated the average degree-day requirement for each life stage from these results, which resulted in 53, 243, 131, 427 and 129 DDCs for egg, larval, pupal, egg-to-adult and pre-oviposition to 50% oviposition stages, respectively. The estimated generation time was 556 DDs, which is the sum of egg-to-adult and 50% oviposition stages.

We set the upper developmental threshold to 35°C based on evidence that the development rate is non-linear (above the optimum) at 30°C for larvae but not for pupae (Dochkova 1972). Taha et al. (2012) observed linear development responses for all stages up to 30°C, but no study reported attempts to rear any stage above this temperature. Additionally, *A. gamma* requires significant humidity (best above 70%; Dochkova 1972), and we consider high temperatures as a proxy for low humidity, particularly for the western U.S.

Emergence parameters.—Autographa gamma overwinters primarily as mid-instar larvae or pupae, and it has no true diapause (Sullivan and Molet 2014). We assumed that seven cohorts of larvae begin pupating in the spring according to a normal distribution (average = 160 DDCs, range = 36–231 DDCs; Table 1). These values were derived primarily by analyzing recent climate data together with trapping data presented by Duthie 1983 and Moths of Northamptonshire (http://www.northamptonshiremoths.org.uk/2441.htm). According to this analysis, the average and peak times of first arrival of migratory moths to central England in the spring (late May) was estimated as 200 and 324 DDC, respectively. We assume that, like England, first moths in northern parts of the coterminous U.S. (CONUS; *ca.* north of Oklahoma, see ‘Climate suitability model’) would be a result of migration from southern sources. We are seeking to improve upon these estimates once we locate additional spring trapping data from temperate regions.

Climate suitability model

Background and Objective

Venette et al. (2003) conducted a risk assessment for *A. gamma* in CONUS based on matching biomes that the species occupies in its native range. However, we are unaware of any published climate suitability modeling studies of the species. Our objective was to parameterize a climate suitability model for *A. gamma* in CLIMEX and DDRP. This involved fitting a CLIMEX model for the species in the native range and using model predictions for CONUS to help parameterize the DDRP model. We were interested in identifying areas of CONUS that may allow for overwintering survival and long-term persistence, compared to areas where temporary establishment may occur only during the growing season.

Methods

CLIMEX model.—We used locality records from GBIF to help fit a CLIMEX model for *A. gamma* in its native range (2 June 2020; GBIF Occurrence Download https://doi.org/10.15468/dl.hje3bv; Fig. 1). We gathered several additional locality records from the literature to better sample the hottest parts of the species' distribution in Africa and the Middle East. We applied a top-up irrigation (additional simulated rainfall) rate of 2.5 mm day^{-1} for the winter and summer season because irrigation mitigates the hot-dry climate that limits the distribution of *A. gamma* within CLIMEX (e.g. in northern Africa, where it is widely distributed in agricultural settings). For northern latitudes, we considered areas with an ecoclimatic index (EI) exceeding 20 to be suitable for long-term persistence, and areas with EI < 20 to be suitable only for short-term establishment during the growing season.

The parameters used for the CLIMEX model are reported in Table 2. We set the temperature index parameters DV0 (limiting low), DV1 (lower optimal), DV2 (upper optimal), and DV4 (limiting high) to 8.9, 15, 23, and 35°C, respectively. The lower and upper optimal thresholds were based on observations that 1) reproduction of *A. gamma* in Israel takes place only in late autumn and winter, when mean monthly temperatures fall to 15–20°C (Yathom and Rivnay 1968); 2) adult survival substantially declines at temperatures <15°C and >23°C (Duthie 1983); and 3) larval development slows at temperatures above 23°C (Duthie 1983). Little is known about the species' moisture stress tolerances, so we used CLIMEX models for two other noctuid moths, *Spodoptera exigua* (Zheng et al. 2012) and *S. litura* (Jung et al. 2019), as a basis for parameterizing moisture stress thresholds and rates.

We set the cold stress threshold (TTCS) and rate (THCS) to −1°C and −0.0015, respectively. While eggs and pupae have a rather high cold tolerance (up to −30.0°C and −12.0°C, respectively), prolonged overwintering at higher latitudes is likely limited by the absence of dedicated energy reserves and by a high level of metabolism typical of non-diapausing insects (Duthie 1983, Saulich et al. 2017). Using these settings, we found that predictions of long-term persistence (EI > 20) in northern latitudes (Fig. 1c) were consistent with studies that documented overwintering populations in parts of Romania, Czechia, Benelux countries, and Germany (Figs. 1a and 1c; Duthie 1983, Saulich et al. 2017, Torniainen and Mikonranta 2018). Conversely, areas where cold stress accumulation exceeded *ca.* 50 units were generally predicted to be unsuitable for long-term persistence (EI < 20), including most of Scandinavia, parts of Poland, and the Baltic states (Figs. 1a and 1c). This finding is consistent with reports that *A. gamma* does not survive winters these regions (Duthie 1983, Winiarska 1989, Hill and Gatehouse 1993, Jakubowska 2011).

However, some areas where the species is not known to overwinter were predicted to be suitable for long-term persistence, including Denmark and southern Sweden (Duthie 1983, Hill and Gatehouse 1993). These predictions may be inaccurate; however, small resident populations reportedly overwinter at even higher latitudes in Finland (Kaisila 1962) and Hokkaido, Japan (when snow cover insulation is available; Saito 2007). The literature suggests that northernmost resident populations are small, and increase significantly when migrants arrive (Saulich et al. 2017).

We set the heat stress threshold (TTHS) and rate (THHS) to 38°C and 0.0015, respectively. This resulted in the prediction of suitable conditions (EI > 20) in the hottest areas where *A. gamma* has been documented (Figs. 1b and 1c), including in parts of Algeria, Egypt, Iraq, Saudi Aribia, and Iran. For example, reports of the species throughout all of Egypt (Rahouma 2018) and in Ethiopia except the lowlands (Kravchenko et al. 2015) are consistent with predictions of climatic suitability in these countries.

DDRP model.—A summary of DDRP parameters used for climate suitability modeling is reported in Table 1. DDRP models used a PRISM data set of daily temperature data averaged over 1961−1990, which matches the gridded weather data interval used in CLIMEX. We applied the same cold and heat stress thresholds as the ones used in CLIMEX, and adjusted moderate stress (max1) and severe stress (max2) limits in accordance with CLIMEX products, as follows. We set DDRP's moderate cold stress limit (max1 = 375) to match the approximate boundary where cold stress in CLIMEX exceeded *ca.* 50 units in CONUS (Fig. 2). Areas under moderate cold stress exclusion therefore represent zones where *A. gamma* could temporarily establish after annual migrations (equivalent to areas where CLIMEX predicts EI < 20; Fig. 4a).

Cold stress would be unlikely to completely exclude the species from any area of CONUS because moths can migrate as far north as Greenland in the native range. We therefore set the severe cold stress limit to the highest level of cold stress experienced in CONUS (max2 = 3600). We set the moderate heat stress limit (max1 = 260) to generally match the boundaries where CLIMEX predicted relatively low suitability (EI < 30) due to heat stress (Figs. 3a and 4a). We set the severe heat stress limit (max2 = 600) so that *A. gamma* was excluded only from extremely hot areas (e.g. Death Valley, California), consistent with CLIMEX.

DDRP results for CONUS

DDRP predicted that *A. gamma* may persist year-round at latitudes below *ca.* 38°N in the East (i.e. south of Kansas except for parts of the eastern seaboard), and in most parts of the Southwest, California, Oregon, and Washington (Fig. 4b). These areas may therefore serve as sources of migrants to regions of CONUS where the species could not survive winters, such as in the Great Basin, Rocky Mountains region, and the upper Midwest and Northeast. Heat stress plays a minimal role in shaping the species' potential distribution, although moderate heat stress may temporarily exclude it from parts of southeastern California and southwestern Arizona.

Suggested applications

The DDRP model may be run to test where *A. gamma* may become established and reproduce in CONUS under current and future weather conditions, and to estimate the dates when specific pest events will occur. For example, predictions of the date when adults begin egg laying for one or more generations may guide APHIS supported Cooperative Agricultural Pest Survey (CAPS) trapping 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 of the overwintered generation (Fig. 5), and (b) potential voltinism (number of generations) with severe stress exclusion (Fig. 6). Understanding whether an area is at risk of long-term establishment (no climate stress exclusions) could help with planning management actions to reduce overwintering survival, such as removing potential plant hosts after crop harvesting.

Improvements needed

The true geographic limit to overwintering survival of *A. gamma* is unclear, which raises the possibility that DDRP cold stress parameters may need adjustments as more data become available. In particular, DDRP may underpredict areas where the species could permanently establish if cold stress parameters are too stringent, or in situations where snow cover facilitates overwintering survival (Saito 2007). Additional spring trapping data from temperate regions are needed to refine estimates of spring pupation and adult flight.

The duration of larval development and of pre-oviposition in *A. gamma* are affected by photoperiod (Hill and Gatehouse 1993, Saito 2007), which suggests that photoperiod additions to DDRP may improve the accuracy of phenology model predictions. Finally, the species has overlapping generations and DDRP does not currently have a capability for this such as by using a distributed delay function. Thus, DDRP may accurately predict peak events in each generation, but inaccurately predict the first appearance of one or more life stages after the first or second generations because of increasing overlap in generation cohorts.

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Table 1. DDRP parameter values for *Autographa gamma*.

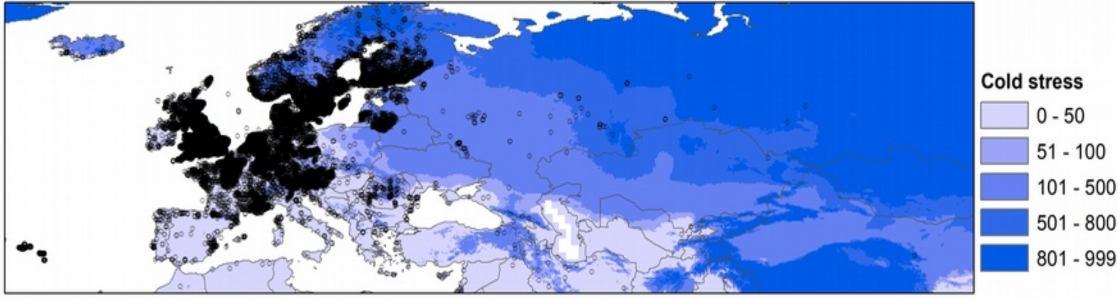
Parameter	Code	Value
Lower developmental thresholds (°C)		
Egg	eggLDT	8.89
Larvae	larvaeLDT	8.89
Pupae	pupaeLDT	8.89
Adult	adultLDT	8.89
Upper developmental thresholds (°C)		
Egg	eggUDT	35
Larvae	larvaeUDT	35
Pupae	pupaeUDT	35
Adult	adultUDT	35
Stage durations (°C degree-days)		
Egg	eggDD	53
Larvae	larvaeDD	243
Pupae	pupDD	131
Adult	adultDD	129
Pest events (°C degree-days)		
Egg event (egg hatch)	eggEventDD	53
Larva event (mid-larval development)	larvaeEventDD	122
Pupa event (mid-pupal development)	pupaeEventDD	65
Adult event (first catch in traps)	adultEventDD	33
Cold stress		
Cold stress temperature threshold (°C)	coldstress_threshold	−1
Cold degree-day (°C) limit when most individuals die	coldstress_units_max1	375
Cold degree-day (°C) limit when all individuals die	coldstress_units_max2	3600
Heat stress		
Heat stress temperature threshold (°C)	heatstress_threshold	38
Heat stress degree-day (°C) limit when most individuals die	heatstress_units_max1	260
Heat stress degree-day (°C) limit when all individuals die	heatstress_units_max2	600
Cohorts		
Avg. degree-days (°C) to OW larvae first pupation	distro_mean	160
Var. in degree-days (°C) to OW larvae first pupation	distro_var	5000
Minimum degree-days (°C) to OW larvae first pupation	xdist1	36
Maximum degree-days (°C) to OW larvae first pupation	xdist2	231
Shape of the distribution of degree-days (°C) to OW pupation	distro_shape	normal

Table 2. Parameter values used in the CLIMEX model for *Autographa gamma*.

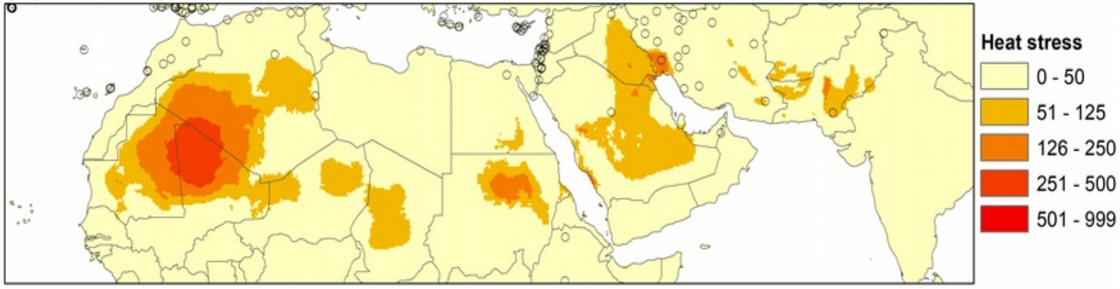
CLIMEX parameter	Code	Value
Temperature		
Lower temperature threshold (°C)	DV0	8.9
Lower optimal temperature (°C)	DV1	15
Upper optimal temperature (°C)	DV2	23
Upper temperature threshold (°C)	DV3	35
Degree-days per generation (°C days)	PDD	556
Moisture		
Lower soil moisture threshold	SM0	0.05
Lower optimal soil moisture	SM1	0.1
Upper optimal soil moisture	SM2	1.0
Upper soil moisture threshold	SM3	2.0
Cold stress		
Cold stress temperature threshold (°C)	TTCS	−1
Cold stress temperature rate (week^{-1})	THCS	−0.0015
Heat stress		
Heat stress temperature threshold (°C)	TTHS	38
Heat stress temperature rate (week^{-1})	THHS	0.0015
Dry stress		
Dry stress threshold	SMDS	0.05
Dry stress rate (week^{-1})	HDS	−0.0001
Wet stress		
Wet stress threshold	SMWS	2.5
Wet stress rate (week^{-1})	HWS	0.002

Fig. 1. Comparison of CLIMEX maps of (a) cold stress, (b) heat stress, and (c) the ecoclimatic index (EI) for *Autographa gamma* (SLYM) in its native range in Europe, North Africa, and Asia. Open circles are locality records used for model fitting.

(a) CLIMEX cold stress



(b) CLIMEX heat stress



(c) CLIMEX ecoclimatic index

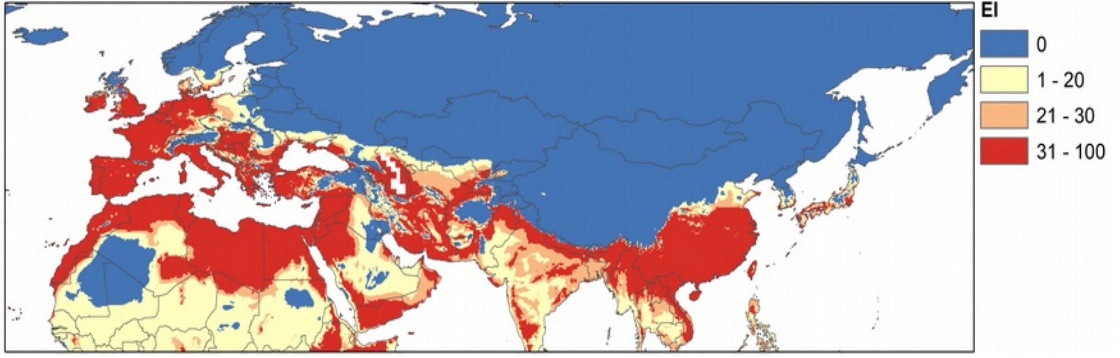
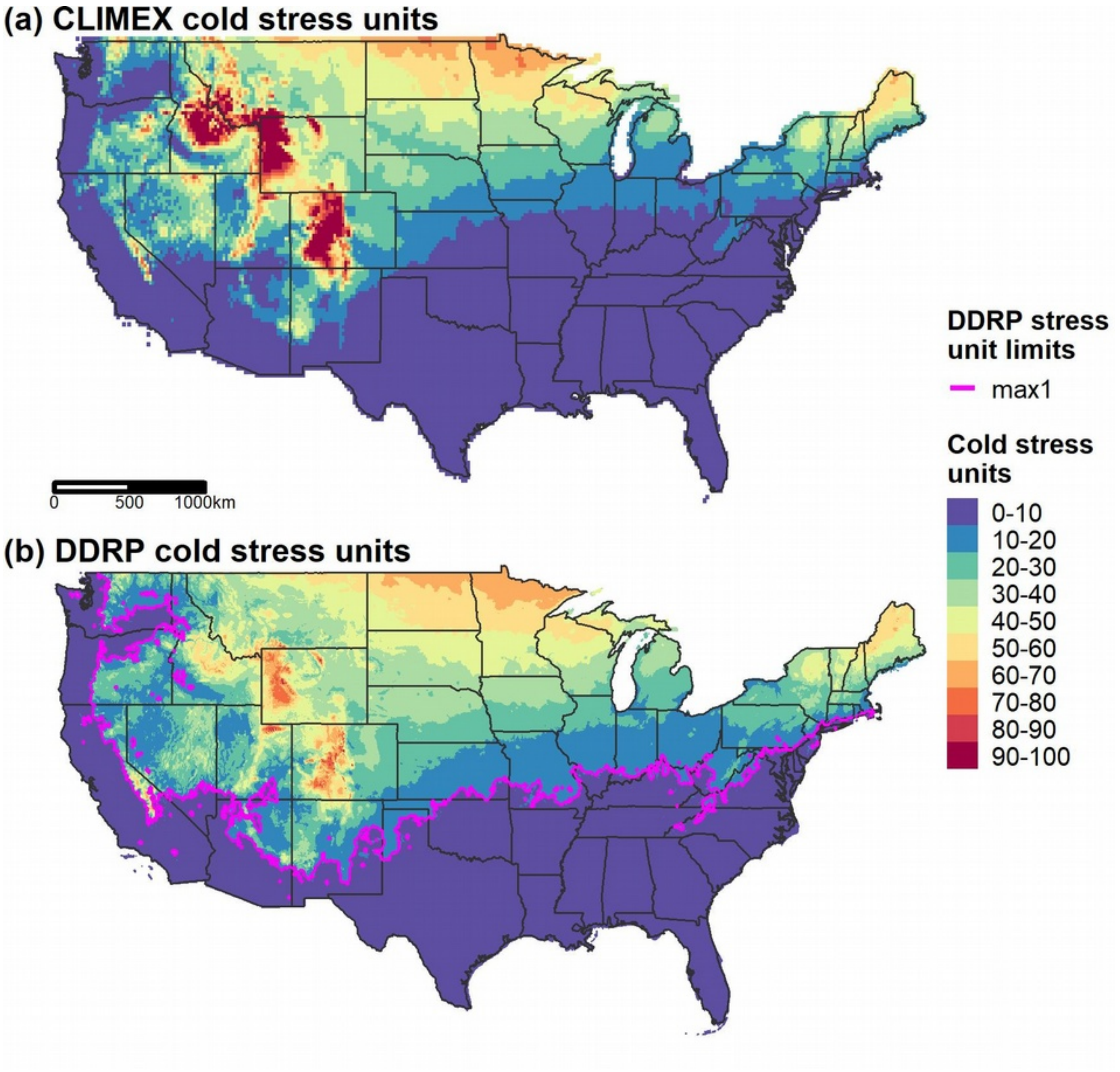


Fig. 2. Maps of cold stress units for *Autographa gamma* (SLYM) produced by (a) CLIMEX and (b) DDRP (cold stress temperature threshold = −1ºC). Cold stress units have been scaled from 0 to 100. Reference climate data for DDRP were from 1961−1990 Normals (matched to available CLIMEX data). The pink line in (b) depicts the cold stress unit limit 1 (375 CSUs).



(a) CLIMEX cold stress units

(b) DDRP cold stress units

Fig. 3. Maps of heat stress units for *Autographa gamma* (SLYM) produced by (a) CLIMEX and (b) DDRP (heat stress temperature threshold = 38ºC). Heat stress units have been scaled from 0 to 100. Reference climate data for DDRP were from 1961–1990 Normals (matched to available CLIMEX data). The pink and blue lines in (b) depict the heat stress unit limits 1 and 2 (260 and 600 CSUs, respectively).

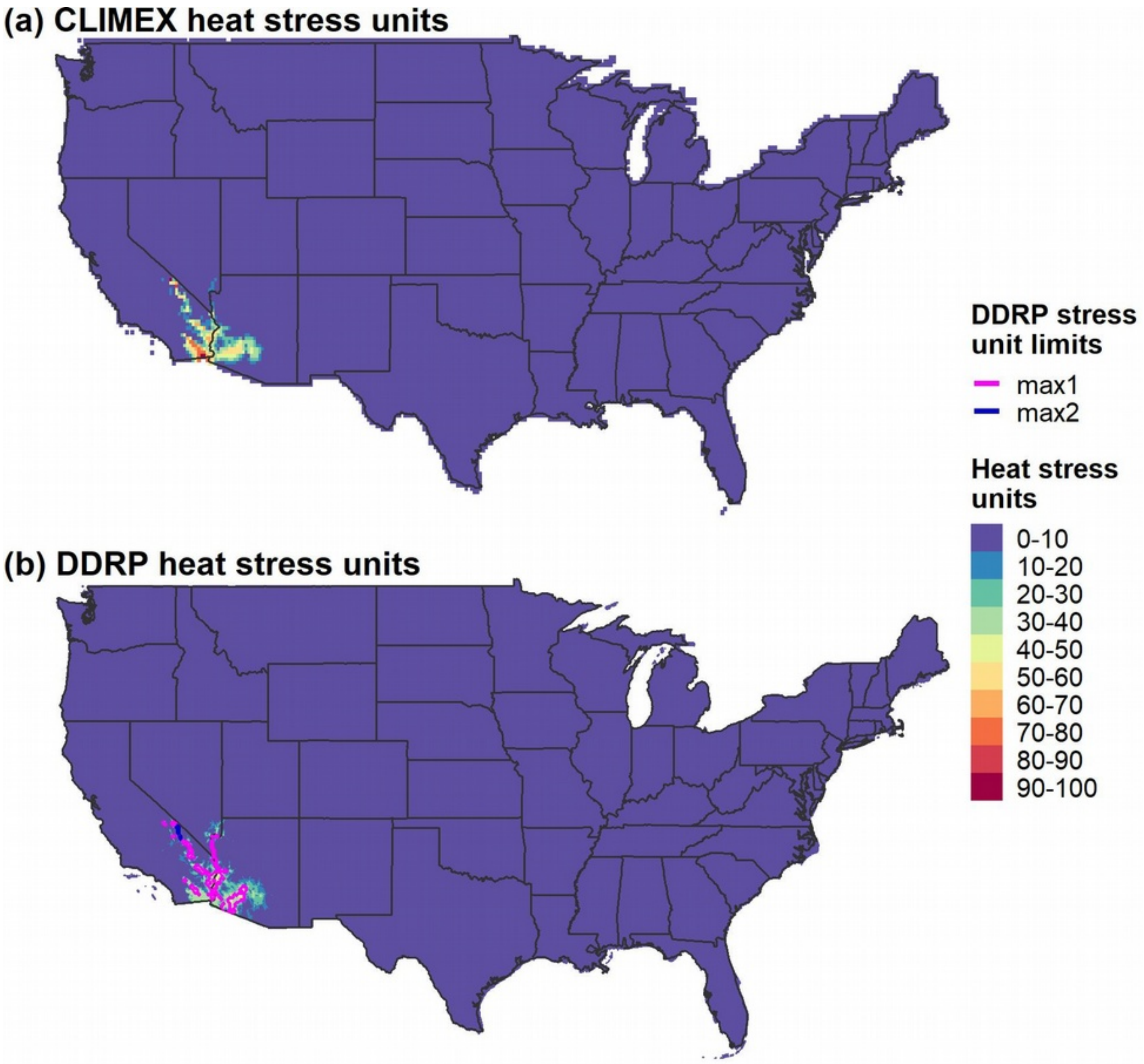
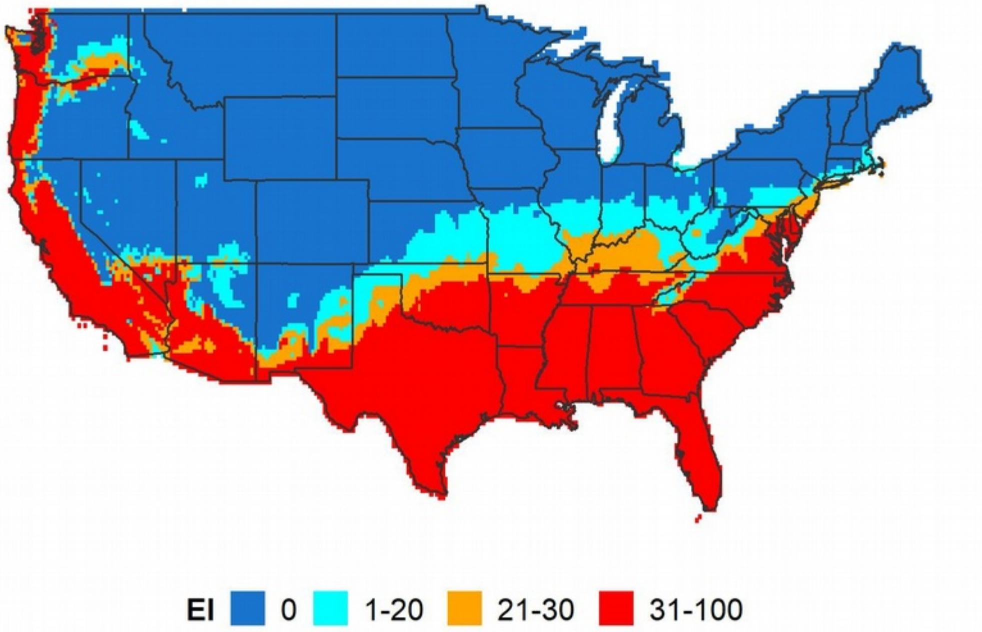


Fig. 4. Climate suitability models *Autographa gamma* (SLYM) in CONUS produced by (a) CLIMEX and (b) DDRP. Areas where CLIMEX predicted suitable conditions (EI > 20) and DDRP predicted no climate stress exclusions may support long-term persistence of populations, and therefore serve as sources of migrants to the rest of CONUS. Reference climate data for DDRP were from 1961–1990 Normals (matched to available CLIMEX data).

(a) CLIMEX ecoclimatic index



(b) DDRP all stress exclusion

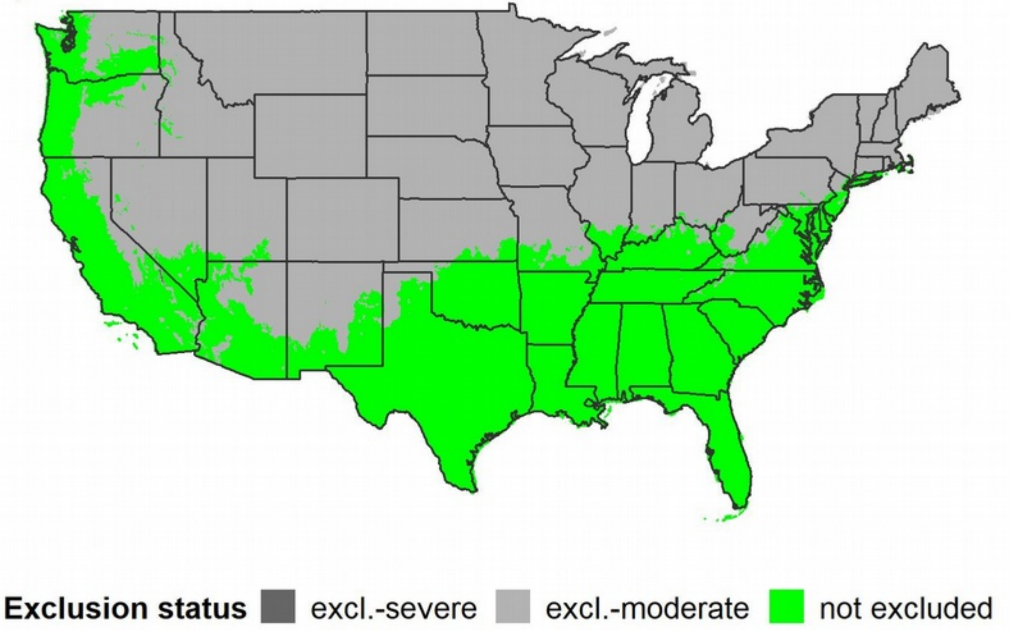


Fig. 5. Map depicting the average date of first egg laying of the overwintered generation of *Autographa gamma* (SLYM) with severe climate stress exclusion for 2012 produced by DDRP. Severe cold stress was not predicted for any part of CONUS because moths would migrate to relatively cold, northern states in the spring.

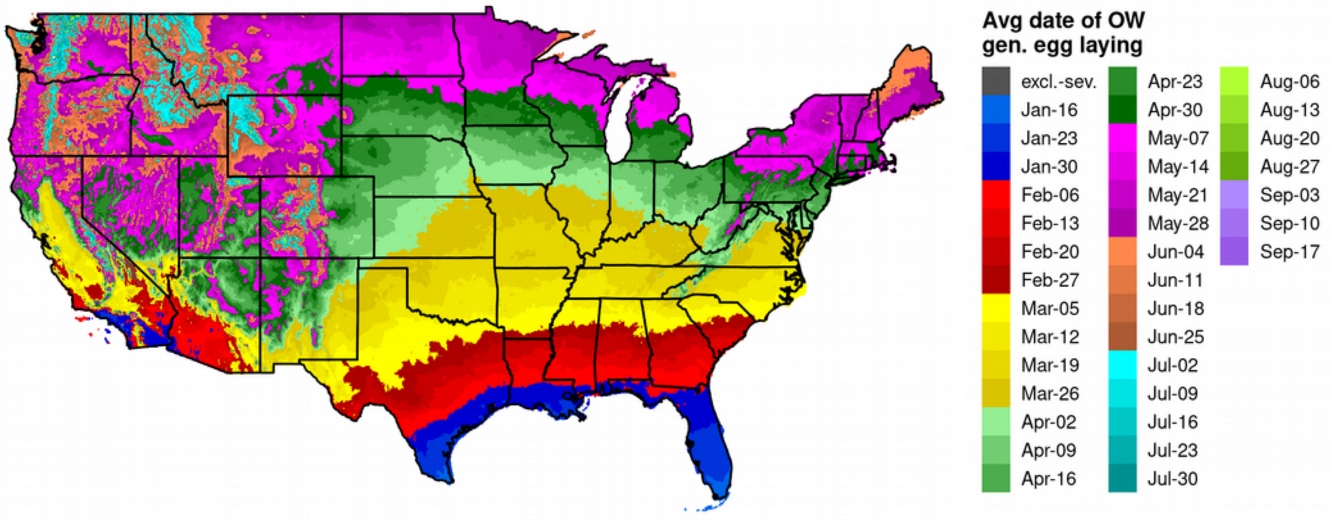


Fig. 6. Map showing the voltinism (number of generations) of *Autographa gamma* (SLYM) with severe climate stress exclusion (based on cold and heat stress units) for 2012 produced by DDRP. Severe cold stress was not predicted for any part of CONUS because moths would migrate to relatively cold, northern states in the spring.