Egyptian Cottonworm

Spodoptera littoralis **(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 Egyptian cotton worm (ECW), *Spodoptera littoralis* (Boisduval), 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; Barker et al. 2020).

Introduction

Spodoptera littoralis is considered one of the most destructive agricultural pests within subtropical and tropical zones of Africa (including Madagascar) and the Mediterranean Basin (CABI 1996). With a host range of over 40 plant families, *S. littoralis* is a major pest of cotton, maize, potato, rice, soybean, vegetables and greenhouse grown ornamentals (CABI 1996, Ellis 2004). Its range extends across the Palearctic region from Africa and southern Europe, and the Arabian Peninsula into Iran. *Spodoptera littoralis* has an allopatric distribution to its sister species, *S. litura*, which occurs throughout Asia and is a similarly destructive agricultural pest (Ellis 2004). The species is not known to be established in the United States, but there have been at least 65 reported incidents of since 2004.

Phenology model

Objective.—We estimated rates and degree days of development in *S. littoralis* 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 *S. littoralis* that is available online at http://uspest.org/wea/Spodoptera_littoralis_model.pdf (Coop and Barker 2020). A summary of phenology model parameters is reported in Table 1. The pest overwinters as late instar larvae or pupa in the soil (pupae are the most cold-resistant stage) and it does not undergo diapause (Miller 1977, Ellis 2004). It may have from two to seven generations per year depending on the climate (Salem and Salama 1985).

We solved for a common lower threshold of 11.67°C for immature stages (eggs, larvae, pupae) and female adults (pre-oviposition to 50% oviposition) by using the x-intercept method to analyze laboratory-based development data presented by Baker and Miller (1974; all immature stages), Bhatt and Bhattacharya (1976; larvae), El-Malki (2000; all stages plus generation time), Nasr and Nassif (1974; all stages plus generation time), Ocete Rubio (1984; immature stages plus generation time), Rivnay and Meisner (1966; pupae), and Sidibe and Lauge (1977; larvae). We calculated the average degree-day requirement for each life stage from these results, which resulted in 49, 236, 152, 437 and 25 DDCs for egg, larval, pupal, egg-to-adult and pre-oviposition to 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 35°C for all life stages (Rivnay and Meisner 1966, Nasr and Nassif 1974, Sidibe and Lauge 1977, Ocete Rubio 1984). Sidibe and Lauge (1977) and Nasr and Nassif (1974) reported that development of larvae slowed at temperatures above 30°C, but using an upper threshold of 35°C is more representative of all stages, and helps account for mitigating behavioral responses, such as a tendency to seek cooler micro climates.

Emergence parameters.—We assumed seven cohorts emerged in the spring according to a normal distribution, with an average (peak) emergence of 242 DDCs (range = 88–396 DDCs; Table 1). These values were chosen based on monitoring studies of *S. littoralis* in Beni Suef Governorate, Egypt (Salem and Salama 1985) and in Cyprus (Campion et al. 1977). Daily climate data from the two study areas were not available, so we selected climatically similar areas in North America to calculate degree-day averages over recent years. As a proxy for Egypt, we calculated average degree-day accumulation between Jan 1 and Mar 2 for 2009–2020 at five sites in Mexico, Louisiana, and Florida. As a proxy for Cyprus, we calculated average accumulations between Jan 1 and Mar 8 for 2013–2020 at four sites in California and Texas. We used the lowest average across the stations as a conservative estimate of peak flight, and this yielded similar results for both analyses (235 vs. 230 DDC). As the Ellis 2004 yielded a slightly higher result of 270 DD, we settled for a weighted average of 240DD. The lower estimate of emergence (xdist1) was derived by subtracting the degree-day requirement for pupae from estimates of peak flight based on the degree-day analysis for Cyprus, while the upper estimate (xdist2) was calculated by adding an addition 33% of the generation time (egg-to-egg; 0.33 × 462 DDC = 154 DDC) to the peak estimate.

Climate suitability model

Background and Objective

Venette et al. (2003) conducted a risk assessment for *S. littoralis* in the contiguous U.S. (CONUS) based on matching biomes that the species occupies in its native range (the publication is no longer available on the internet). However, we are unaware of any published climate suitability modeling studies of the species. Our objective was to parameterize a climate suitability model for *S. littoralis* 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. The species typically migrates only over short distances, although it is capable of long-distance migration (Campion et al. 1977).

CLIMEX model

*Methods.—*We used locality records from GBIF (4 November 2020; GBIF Occurrence Download https://doi.org/10.15468/dl.avwfk5) and the literature to help fit a CLIMEX model for *S. littoralis* in the Old World. 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 *S. littoralis* within CLIMEX (e.g. in northern Africa, where it is widely distributed in agricultural settings).

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 11.7, 17, 30, and 35°C, respectively. DV0 and DV4 were defined based on the phenology developed for this study. The DV1 and DV2 parameters are based on studies showing that survival of larvae and pupae decline at temperatures <20°C (Rivnay and Meisner 1966, Bhatt and Bhattacharya 1976), survival to adulthood is highest at 20–25°C (Ocete Rubio 1984), and egg viability and larval development declines at temperatures >30°C (Nasr and Nassif 1974, Sidibe and Lauge 1977, Khafagi et al. 2016).

We set the cold stress threshold (TTCS) and rate (THCS) to 10°C and –0.0007, respectively. The species exhibits high mortality at temperatures ≤13°C (Rivnay and Meisner 1966, Powell and Gostick 1971, Miller 1977), and winter temperatures that drop below 13.5°C for more than 70 days were associated with a lack of overwintering survival in southern France and northern Italy (Miller 1977). However, we used an even lower threshold (10°C) because there is ample evidence that development may still occur at 13°C (see multiple sources cited here and in the spreadsheet analysis). Additionally, our cold stress parameter combination (i.e. TTCS = 10°C and THCS = –0.0007) resulted in predictions of long-term establishment [Ecoclimatic Index (EI) > 0] in the same areas documented by Miller (1977) and by other reports (reviewed in EFSA Panel on Plant Health 2015; Fig. 1). These areas occur in Cyprus and the southernmost areas of Spain, Italy, Greece and France (Miller 1977, EFSA Panel on Plant Health 2015).

Relatively little is known about the tolerance of *S. littoralis* to heat, wet, and dry stress. The species has high mortality and will not reproduce when temperatures exceed 37°C (Rivnay and Meisner 1966) so we set the heat stress threshold (TTHS) to 37°C. This resulted in the inclusion of the hottest areas where the species is common and widespread in the potential distribution (e.g., very hot parts of Africa and the Middle East; Fig. 1). 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 evaluated the predictive performance of the CLIMEX model by determining whether EI values from locality records from non-migratory populations were greater than 0. We assumed that records from northern parts of Europe including the United Kingdom and northern France represented temporary (or possibly indoor) populations. We removed records from islands because many were missing results owing to the coarse spatial resolution of the climate data.

Results.—CLIMEX predicted the potential for long-term establishment (EI > 0) throughout the known range of *S. littoralis* in the Old World including most of Africa, the Middle East, southernmost parts of Southern Europe, and parts of southern Asia (Pakistan and India; Fig. 1). Of 146 records derived from putatively non-migratory populations, 132 (90.4%) had an EI > 0. We cannot rule out the possibility that the erroneously excluded records were collected from temporary populations (e.g., some were collected from relatively cold parts of South Africa).

In Europe, areas that were included in the potential distribution (i.e. long-term establishment) were characterized by annual cold stress accumulations of <100 units (Fig. 1). Fifty one locality records (GBIF) from northern Europe occurred in areas where EI = 0, of which 40 occurred in areas where cold stress did not exceed 300 units. These findings suggest that long-term establishment is prevented when cold stress accumulations exceed *ca.* 100 cold stress units, whereas short-term establishment predominantly occurs in areas that do not accumulate >300 units. Cold stress was the major range-limiting factor for *S. littoralis* in both the Old World and CONUS, whereas heat stress did not significantly shape the potential distribution (Figs. 2 and 3). Long-term establishment (EI > 0) was predicted only in southern parts of California, Arizona, Georgia, South Carolina, and the Gulf Coast states (Alabama, Florida, Louisiana, Mississippi, and Texas; Fig. 4). Temporary establishments may occur as far north as *ca.* 39°N in the East, and throughout most of California.

<u>DDRP climate suitability model</u>

Methods.—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 assumed that *S. littoralis* would not be excluded from areas in CONUS where EI > 0. We set DDRP's moderate and severe cold stress limits (max1 = 950, max 2 = 2250 units) to match the approximate boundary where cold stress in CLIMEX exceeded 100 units and 300 units, respectively (Figs. 2 and 3). Thus, areas under moderate cold stress exclusion (i.e. between 950 and 2250 units) represent zones where *S. littoralis* could temporarily establish. We used high moderate (max1 = 800) and severe (max2 = 1100) heat stress limits (Fig. 3) owing to the minor role that heat stress appears to play in shaping the species' distribution according to CLIMEX.

Results.—DDRP predicted long-term establishment of *S. littoralis* in the same areas as CLIMEX, although a somewhat larger area of the Gulf Coast states (coastline areas) and California were included in the potential distribution (Fig. 4). Similarly, DDRP predicted moderate cold stress exclusion in the same areas where CLIMEX predicted the potential for short-term establishment, except that parts of western Oregon and Washington were also included. Severe cold stress is predicted to permanently exclude the species from the Mountain West, most of the Midwest, and the Northeast. Heat stress in southeastern California and southwestern California was not high enough to exclude *S. littoralis* with the possible exception of the vicinity of Death Valley.

Suggested applications

The DDRP model may be run to test where *S. littoralis* may become established and reproduce in CONUS under current and future climatic conditions, and to estimate the dates when specific pest events will occur. For example, predictions of the date of adult activity (flight and 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. Conversely, predictions of moderate cold stress exclusions may provide insight into whether *S. littoralis* could expand northward during relatively mild winters.

Improvements needed

The role of heat stress in limiting the distribution of *S. littoralis* in the Old World is not well understood, so DDRP heat stress parameters will likely need adjustments as more data become available. Data on the impacts of moisture on development and survival are needed to inform moisture stress parameters in CLIMEX. The analysis of degree-day data from actual areas where the species occurs (rather than data from similar climates in North America) may help refine estimates of spring pupation and adult flight.

References

Baker, C. R. B., and G. W. Miller. 1974. Some effects of temperature and larval food on the development of *Spodoptera littoralis* (Boisd.) (Lep., Noctuidae). Bulletin of Entomological Research 63:495–511.

Barker, B. S., L. Coop, T. Wepprich. F., Grevstad, G. Cook. 2020. DDRP: Real-time phenology and climatic suitability modeling of invasive insects. PLoS ONE 15(12): e0244005. https://doi.org/10.1371/journal.pone.0244005

Bhatt, N. S., and A. K. Bhattacharya. 1976. Development of *Spodoptera littoralis* (Boisd.) (Lep., Noctuidae) at constant temperatures on two host plants. Zeitschrift für Angewandte Entomologie 80:201–206.

CABI. 1996. EPPO data sheets on quarantine pests: *Spodoptera littoralis* and Spodoptera litura.

Campion, D. G., B. W. Bettany, J. B. McGinnigle, and L. R. Taylor. 1977. The distribution and migration of *Spodoptera littoralis* (Boisduval) (Lepidoptera: Noctuidae), in relation to meteorology on Cyprus, interpreted from maps of pheromone trap samples. Bulletin of Entomological Research 67:501–522.

EFSA Panel on Plant Health. 2015. Scientific opinion on the pest categorisation of *Spodoptera littoralis*. EFSA Journal 13:1–26.

El-Malki, K. G. 2000. Thermal requirements and prediction models of cotton leafworm *Spodoptera littoralis* (Boisd). 2000 Proceedings Cotton Conferences Vol. 2 2:1019–1021.

Ellis, S. E. 2004. New Pest Response Guidelines: *Spodoptera*. USDA/APHIS/PPQ/PDMP. Animal and Plant Health Inspection Service, Plant Protection and Quarantine.

Jung, J.-M., D. Byeon, S. Jung, and W.-H. Lee. 2019. Effect of climate change on the potential distribution of the common cutworm (*Spodoptera litura*) in South Korea. Entomological Research 49:529–528.

Miller, G. W. 1977. Mortality of *Spodoptera littoralis* (Boisduval) (Lepidoptera: Noctuidae) non-freezing temperatures. Bulletin of Entomological Research 67:142–152.

Nasr, E.-S., and F. M. Nassif. 1974. Response of various stages of the cotton leafworm, *Spodoptera littoralis* (Boisd.) to temperature and relative humidity. Bulletin de la Société entomologique d’Égypte 58:123–131.

Ocete Rubio, E. 1984. Study of the biological cycle of *Spodoptera littoralis* (Boisduval) at different temperatures. Graellsia 40:195–206.

Powell, D. F., and K. G. Gostick. 1971. Control of *Spodoptera littoralis* (Boisd.), *Myzus persicae* (Sulz.) and *Tetranychus urticae* (Koch) by cold storage and fumigation. Bulletin of Entomological Research 61:235–240.

Rivnay, E., and J. Meisner. 1966. The effects of rearing conditions on the immature stages and adults of *Spodoptera littoralis* (Boisd.). Bulletin of Entomological Research 56:623.

Salem, S., and H. S. Salama. 1985. Sex pheromones for mass trapping of *Spodoptera littoralis* (Boisd.) in Egypt. Zeitschrift für Angewandte Entomologie 100:316–319.

Sidibe, B., and G. Lauge. 1977. Incidence of contsant temperature conditions and thermoperiods on some biological features of *Spodoptera littoralis* Boisduval. Annals of the Entomoogical Society France 13:369–379.

Venette, R. C., E. E. Davis, H. Heisler, and M. Larson. 2003. Mini risk assessment, Egyptian cotton leafworm, *Spodoptera littoralis* (Lepidoptera: Noctuidae). Cooperative Agricultural Pest Survey, Animal and Plant Health Inspection Service, U.S. Department of Agriculture.

Zheng, X.-L., P. Wang, W.-J. Cheng, X.-P. Wang, and C.-L. Lei. 2012. Projecting overwintering regions of the beet armyworm, *Spodoptera exigua* in China using the CLIMEX model. Journal of Insect Science 12:1–13.

Table 1. DDRP parameter values for *Spodoptera littoralis*.

Parameter	Code	Value
Lower developmental thresholds (°C)		
Egg	eggLDT	11.67
Larvae	larvaeLDT	11.67
Pupae	pupaeLDT	11.67
Adult	adultLDT	11.67
Upper developmental thresholds (°C)		
Egg	eggUDT	35
Larvae	larvaeUDT	35
Pupae	pupaeUDT	35
Adult	adultUDT	35
Stage durations (°C degree-days)		
Egg	eggDD	49
Larvae	larvaeDD	236
Pupae	pupDD	152
Adult	adultDD	25
Pest events (°C degree-days)		
Egg event (egg hatch)	eggEventDD	49
Larva event (mid-larval development)	larvaeEventDD	118
Pupa event (mid-pupal development)	pupaeEventDD	76
Adult event [adult activity (flight/egg laying)]	adultEventDD	25
Cold stress		
Cold stress temperature threshold (°C)	coldstress_threshold	10
Cold degree-day (°C) limit when most individuals die	coldstress_units_max1	950
Cold degree-day (°C) limit when all individuals die	coldstress_units_max2	2250
Heat stress		
Heat stress temperature threshold (°C)	heatstress_threshold	37
Heat stress degree-day (°C) limit when most individuals die	heatstress_units_max1	800
Heat stress degree-day (°C) limit when all individuals die	heatstress_units_max2	1100
Cohorts		
Avg. degree-days (°C) to OW larvae first pupation	distro_mean	242
Var. in degree-days (°C) to OW larvae first pupation	distro_var	5000
Minimum degree-days (°C) to OW larvae first pupation	xdist1	88
Maximum degree-days (°C) to OW larvae first pupation	xdist2	396
Shape of the distribution of degree-days (°C) to OW pupation	distro_shape	normal

Table 2. Parameter values used in the CLIMEX model for *Spodoptera littoralis*.

CLIMEX parameter	Code	Value
Temperature		
Lower temperature threshold (°C)	DV0	11.7
Lower optimal temperature (°C)	DV1	17
Upper optimal temperature (°C)	DV2	30
Upper temperature threshold (°C)	DV3	35
Degree-days per generation (°C days)	PDD	476
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	10
Cold stress temperature rate (week^{-1})	THCS	–0.0006
Heat stress		
Heat stress temperature threshold (°C)	TTHS	37
Heat stress temperature rate (week^{-1})	THHS	0.002
Dry stress		
Dry stress threshold	SMDS	0.05
Dry stress rate (week^{-1})	HDS	–0.00005
Wet stress		
Wet stress threshold	SMWS	2.5
Wet stress rate (week^{-1})	HWS	0.002

Fig. 1. CLIMEX maps of (a) cold stress, (b) heat stress, and (c) the ecoclimatic index (EI) for *Spodoptera littoralis* (ECW) in the Old World. Locality records (teal circles) were derived from the literature and GBIF. Localities where the species is known to overwinter (yellow circles; Miller 1977) all had cold stress accumulations below 100 units. OW = overwintering documented; No OW = migratory populations only.

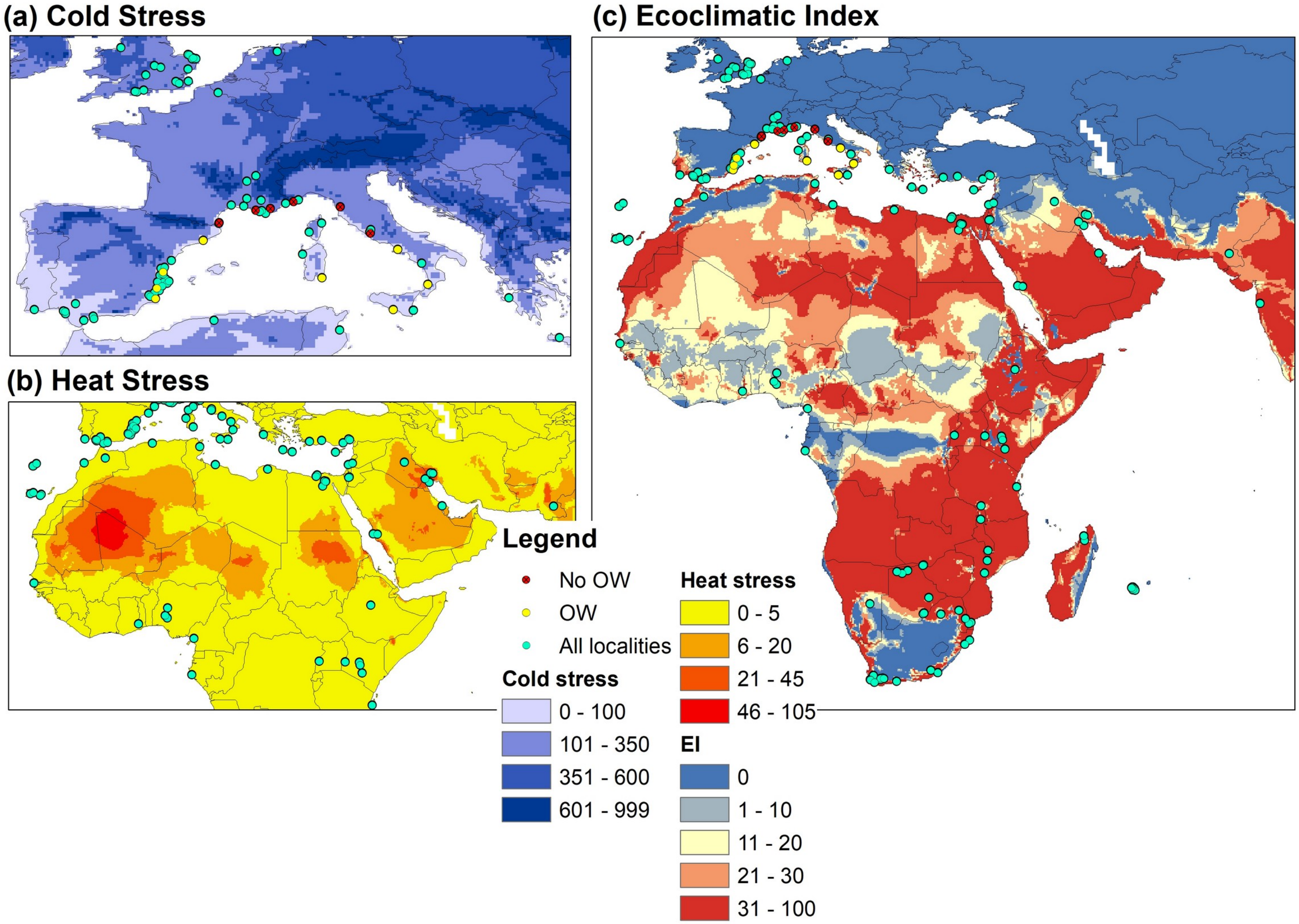
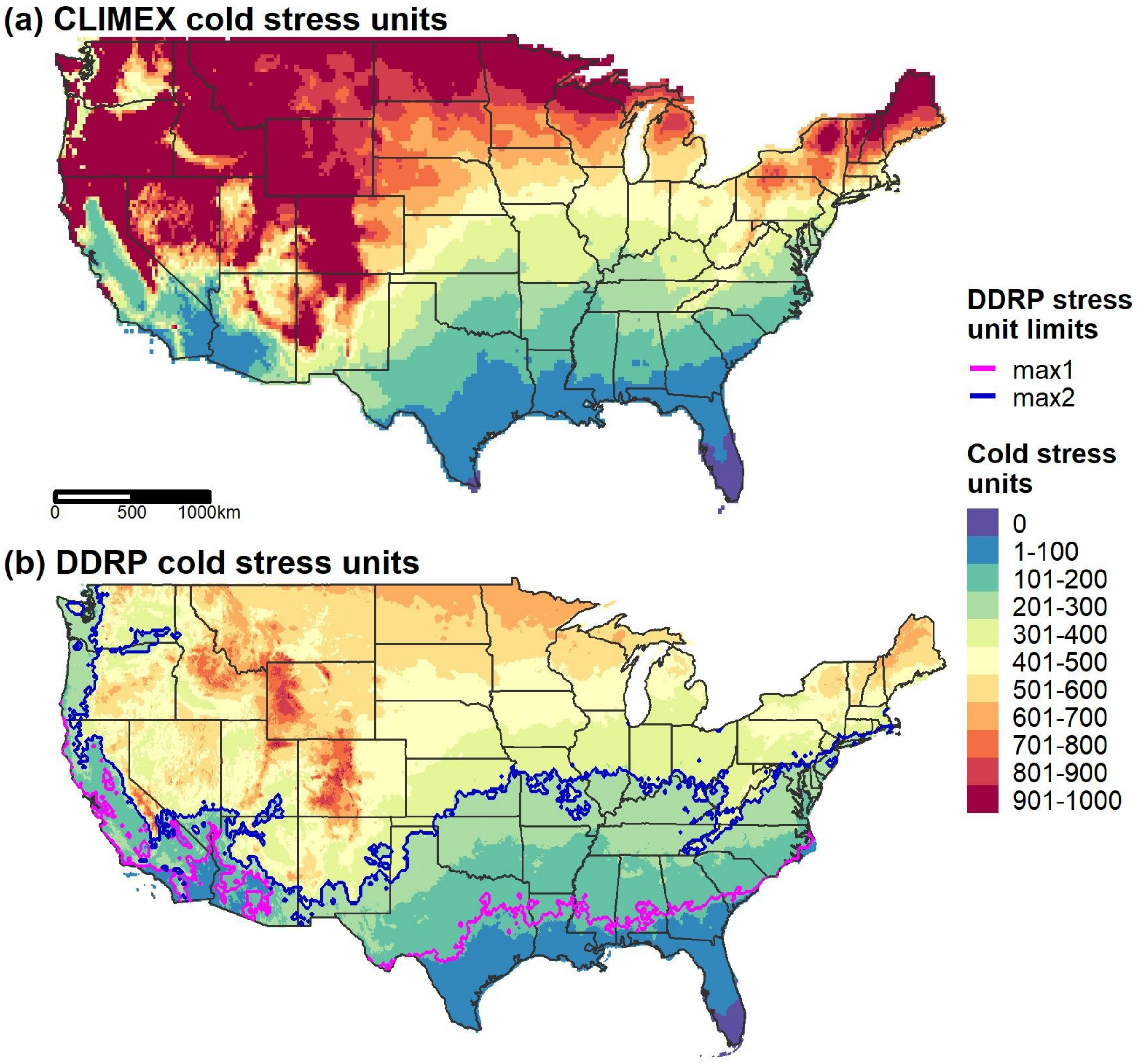


Fig. 2. Maps of cold stress units for *Spodoptera littoralis* (ECW) produced by (a) CLIMEX (cold stress temperature threshold, TTCS = 10ºC) and (b) DDRP (cold stress temperature threshold = 10ºC). Reference climate data for DDRP were from 1961–1990 Normals (matched to available CLIMEX data). The pink and black lines in (b) depict the cold stress unit limits 1 and 2 (950 and 2250 CSUs, respectively; Table 1).


(a) CLIMEX cold stress units

(b) DDRP cold stress units

Fig. 3. Maps of heat stress units for *Spodoptera littoralis* (ECW) produced by (a) CLIMEX and (b) DDRP (both models used a heat stress temperature threshold of 37ºC). Reference climate data for DDRP were from 1961–1990 Normals (matched to available CLIMEX data). The pink line in (b) depicts the heat stress unit limit 1 (800 HSUs; Table 1).

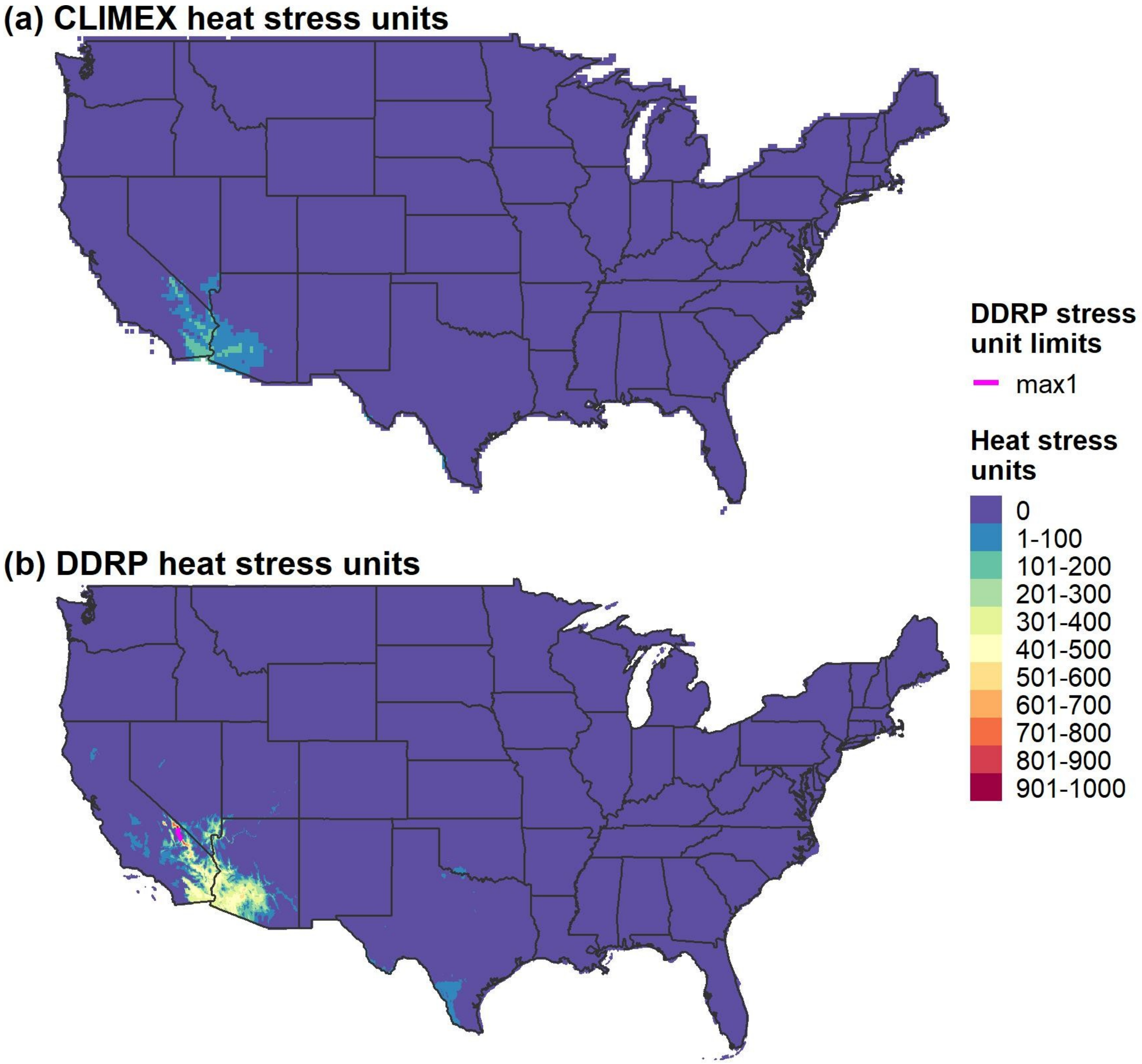
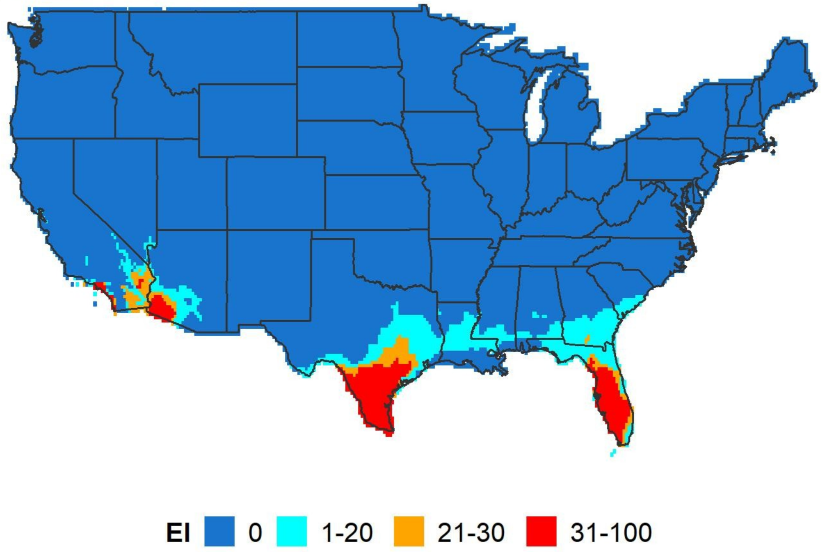


Fig. 4. Climate suitability models for *Spodoptera littoralis* (ECW) in CONUS produced by (a) CLIMEX and (b) DDRP. DDRP measures exclusion status of the species based on cold and heat stress units (all stress exclusion). Both models applied a cold stress threshold of 10ºC and a heat stress threshold of 37ºC. Reference climate data for DDRP were from 1961–1990 Normals (matched to available CLIMEX data).

(a) CLIMEX ecoclimatic index



(b) DDRP all stress exclusion

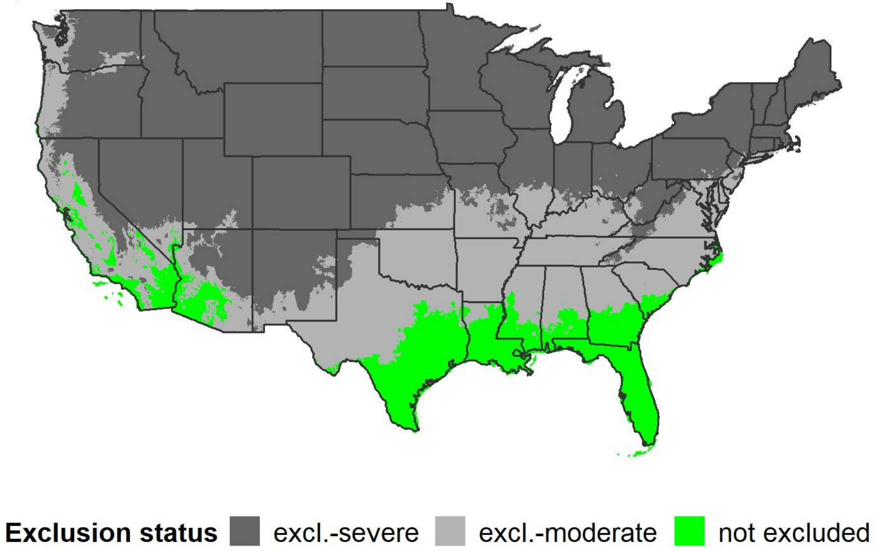


Fig. 5. Map depicting the date of first adult activity (flight and egg laying, averaged across 7 cohorts) of the overwintering generation of *Spodoptera littoralis* (ECW) with moderate and severe climate stress exclusions (based on cold and heat stress units) for 2012 produced by DDRP. Areas under moderate stress exclusion may support short-term establishment during the growing season.

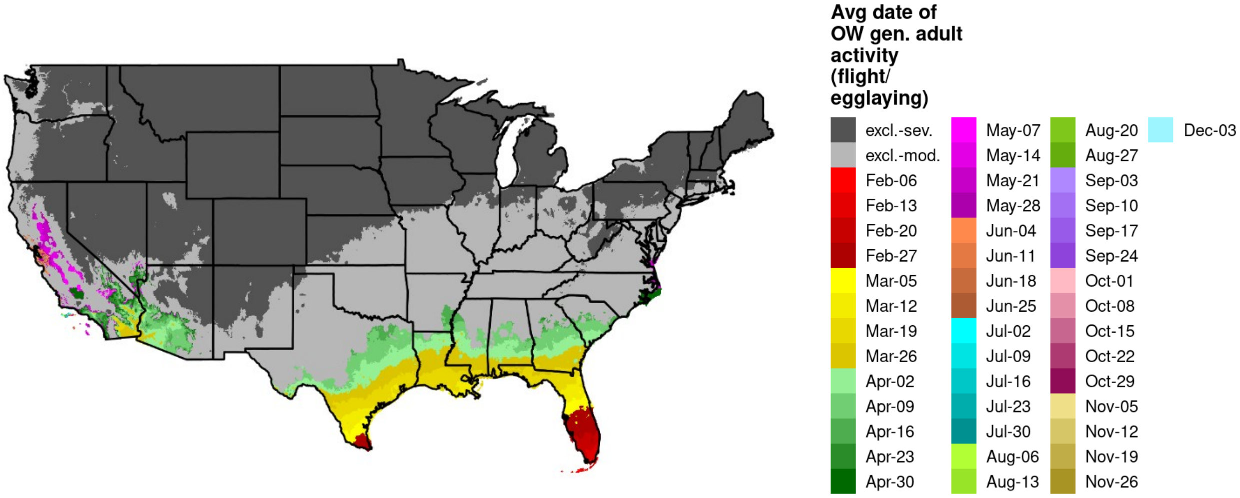


Fig. 6. Map showing the voltinism (number of generations, averaged across 7 cohorts) of *Spodoptera littoralis* (ECW) with severe climate stress exclusion (based on cold and heat stress units) for 2012 produced by DDRP.