Spotted Lanternfly
Lycorma delicatula (Hemiptera: Fulgoridae)

Phenology/Degree-Day and Climate Suitability Model Analysis for USPest.org
Prepared for USDA NIFA AFRI Tactical Sciences for Agricultural Biosecurity (TSAB)
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Summary

A phenology model and temperature-based climate suitability model for the spotted lanternfly (SLF), *Lycorma delicatula* (White) (Hemiptera: Fulgoridae), was developed for the DDRP (Degree-Days, Risk, and Pest event mapping; under development for uspest.org) platform using data from available literature and from occurrence records in online biodiversity databases.

1. Introduction

Lycorma delicatula is a planthopper that feeds across a wide range of economically important plants in forest and agricultural ecosystems, including grape, grape, and stone fruit, as well as plants and trees in nonagricultural habitats (EPPO 2016, Barringer and Ciafré 2020, Uyi et al. 2021). In addition to causing significant economic losses to vineyards, nurseries, and sawmills in invaded areas, *L. delicatula* is a nuisance pest to homeowners and businesses in suburban landscapes (Lee et al. 2019, Urban and Leach 2023). The insect damages plants directly by feeding on plant sap as well as indirectly by excreting honeydew, which can cause sooty mold that impedes photosynthesis of affected plants (Dara et al. 2015, Urban and Leach 2023). Native to China (Chu 1930), *L. delicatula* spread through southeastern Asia over the past 20 years (Han et al. 2008, Kim et al. 2013) and was first detected in the United States in 2014, where it has since spread to at least 14 northeastern states (New York State Integrated Pest Management Program 2023, Urban and Leach 2023).

2. Methods

This is a summary of the spreadsheet analysis that is available online (https://uspest.org/wea/spotted_lanternfly_model.pdf). Final parameters used in the DDRP model are presented in Table 1.

2.1. Phenology model

2.1.1. Life cycle and overwintering stage

The model uses a start date of 1 January and assumes a one-year (univoltine) life cycle in which the egg is the overwintering stage. The model stops after a full life cycle completes (*obligate_diapause* = 1) because of evidence that eggs require a chilling period before development can resume (Shim and Lee 2015, Keena and Nielsen 2021). DDRP models include four separate life stages (egg, larva, pupa, and adult) plus a separately parameterized overwintering stage. To conform to these naming conventions, we defined the nymph stage (instars 1−4) as the “larva,” the pre-oviposition period as the “pupa”, and the 1st to 50% oviposition period as the “adult.”

2.1.2. Temperature thresholds for development

We re-interpreted temperature vs. development rate data for *L. delicatula* from several laboratory studies (Kreitman et al. 2021, Smyers et al. 2021) and monitoring studies (Liu 2019, Leach and Leach 2020, Murman et al. 2020, Nixon et al. 2020, Dechaine and Leskey 2021, Smyers et al. 2021). For lab studies conducted at multiple temperatures, we used linear regression (x-intercept method) with forcing through the x-intercept to estimate the lower temperature threshold and degree-day (DD) requirements for major stages of the species. From these works, we solved for a common lower temperature threshold of 10 °C for eggs, larvae, pupae and egg-to-adult. The results all had high R-squared values, ranging from a low of 0.964 to a high of 0.988, with a combined (instars 1−4) value of 0.996.

2.1.3. Development in degree days

Results including stage durations and first and peak event DD requirements for major stages are reported in Table 1. At a lower threshold of 10 °C, egg, nymphal egg-to-adult and pre-oviposition DD requirements were 202, 890, 1092, and 630 DDs, respectively. First to 50% oviposition was estimated as 146 DDs.

2.1.4. Cohort parameters

Cohort parameters in DDRP allow for variation in the development in overwintered eggs of *L. delicatula*. The model applied seven time-distributed cohorts to approximate a normal distribution of egg hatch times. Several monitoring studies have documented an overall normal distribution in counts of eggs and nymphs during a season (Park 2015, Liu 2019, Dechaine et al. 2021). Egg monitoring data from five sites in Pennsylvania and Virginia, USA (Liu 2019, Leach and Leach 2020, Murman et al. 2020, Nixon et al. 2020, Dechaine et al. 2021, Smyers et al. 2021) were used to calibrate values for the low, average, and high bound values for the minimum (*xdist1*), mean (*distro_mean*), and maximum (*xdist2*) DDs to complete development. This involved running models with different parameter combinations and extracting model predictions for the minimum (earliest) and average (peak) dates of egg hatch for each site/year (N = 15) in the monitoring data. The number of overpredictions (too late) as well as the mean absolute error (MAE) and bias (in days) were estimated from predictions. All models applied the “normal” option for the *distro_shape* parameter and 15,000 DDs for the variance of development completion times. The parameter set that resulted in the fewest number of overpredictions was used in the final model.

2.2. Climate suitability model

A climatic suitability model for *L. delicatula* was developed using eco-physiological information and 392 presence records from China. Records were derived from peer-reviewed literature, theses, reports, and the Global Biodiversity Information Facility (GBIF.org 2022) (http://gbif.org, accessed 19 Jul 2023). Duplicate records, GBIF records with a geographic uncertainty of >10 km, and records that occurred outside of climate grid cells were excluded. Climatic suitability models used daily estimates of T_{min} and T_{max} from the CDAT dataset for 1999 to 2018 at a spatial resolution of 0.1° (Fang et al. 2022)(accessed on 28 June 2022; https://zenodo.org/record/5513811#.YtnLNXbMIuU).

2.2.1. Cold stress parameters

To identify an appropriate cold stress threshold, we extracted estimates of T_{min} of the coldest week for each presence record from China. Daily CDAT data were averaged and then aggregated to a weekly resolution to better reflect longer term (i.e., multi-day) cold stress experienced by *L. delicatulua*, which may survive through extended periods of sub-zero temperatures in the egg stage (Lee et al. 2011, 2014, Park 2015). Eggs are laid on the surface of oviposition substrate and are therefore directly exposed to winter temperatures. According to this analysis, 98% (385/392) of records occurred in areas with average weekly T_{min} values ≥ –16 °C (Fig. 1A). This finding is consistent with monitoring work that revealed very low egg survival rates (<2%) at South Korean sites where average daily T_{min} fell below –16 °C (Park 2015).

The severe cold stress limit in DDRP was set to correspond roughly with areas that experienced more than 14 consecutive days below –16 °C (Fig. 1B). In a laboratory study, mortality rates of cold-acclimated *L. delicatula* eggs dropped from *ca.* 5% to 0% after exposure to –15 °C for seven and 10 days, respectively (Park 2015). Thus, exposure of eggs in the field to more than *ca.* 2 weeks at similar temperatures would likely exhibit significant mortality and therefore limit long-term establishment. We delineated the moderate cold stress limit to correspond roughly with areas that experienced a daily average T_{min} below –16 °C for nine consecutive days. The moderate cold stress limit was further calibrated by minimizing the number of records that were excluded during years in which particularly high levels of cold stress accumulated (2001 and 2005)(Fig. 1C).

After cold stress limit calibrations, two presence records for *L. delicatula* from Jilin Province, China, were excluded by severe or moderate cold stress across multiple (2–11) modeled years. Average weekly T_{min} values at locations for both records were *ca.* –20 °C, which has been estimated as the pest's lower lethal temperature (Park 2015). However, we chose to keep the final parameters because the records lacked precise geographic coordinates and were from a single study (Liu et al. 2015). Additionally, predictions of exclusion by cold stress in most areas north of *ca.* 40° N for multiple modeled years is consistent with surveys indicating that this latitude appears to be the northern range limit for this pest in China (Xin et al. 2021).

2.2.2. Heat stress parameters

Following the same approach used for cold stress parameter calibration, we extracted estimates of T_{max} of the hottest week for each presence record for *L. delicatula*. According to this analysis, 99% (389/392) of records occurred in areas with average weekly T_{max} ≤ 37 °C (Fig. 2).

The remaining three records were from parts of Zhejiang Province where up to four consecutive days above 37 °C occurred during the hottest year in terms of heat stress accumulation (2008) (Figs. 2A and 2B). These findings are consistent with laboratory studies that found high or complete mortality of nymphs after exposure to *ca.* 3 days at 35−40 °C (Kreitman et al. 2021, Keena et al. 2023). We therefore calibrated the moderate heat stress limit to correspond roughly to areas that experienced a daily average T_{max} above 37 °C for more than five consecutive days and to minimize the exclusion of records across all modeled years. The severe heat stress limit was set to correspond roughly with areas that experienced a daily average T_{max} above 37 °C for *ca.* 15 consecutive days.

2.2.3. Estimating the potential distribution

As an estimate of the potential distribution of *L. delicatula* in CONUS, we ran DDRP using the Daymet dataset for the contiguous United States (CONUS) and southern Canada for 2002 to 2021 at a spatial resolution of 1 km^2 (https://daymet.ornl.gov/getdata, accessed 13 July 2022) (Thornton et al. 2021). Areas where the insect was not excluded by moderate or severe stress exclusion for all modeled years would likely be at high risk of establishment.

3. Demonstration

We produced phenological event maps for egg hatch and appearance of adults for *L. delicatula* in 2023 for CONUS to provide insights into its phenology and potential distribution during a particularly warm year. According to an analysis by NASA, the summer of 2023 was the hottest on record for the Northern Hemisphere. Forecasts for nymphs and adults are particularly relevant to surveillance because egg masses are less visible. The model applied seven cohorts.

4. Results and Discussion

The number of overpredicted dates of first egg hatch and peak egg hatch for *L. delicatula* was lowest (N = 2) when the low, average, and high bound values for the completion of egg development were set to 150, 215, and 360 DDC, respectively (Tables 3 and 4). The MAE between predicted and observed DOYs for first and peak egg hatch were 8 and 6.7 days, respectively (Table 3). On average, first egg hatch was underpredicted by 8 days [standard deviation (SD) = 7.1] whereas peak egg hatch was underpredicted by 3.9 days (SD = 7.8). Additional observations collected from across a broader geographic range are needed to further calibrate the cohort parameter values.

DDRP predicted that *L. delicatula* was excluded from the coldest parts of the upper Midwest and northeastern U.S. for most or all of 20 modeled years (Fig. 3), which is consistent with Maxent and CLIMEX model predictions for this pest (Jung et al. 2017, Wakie et al. 2019). Only the hottest parts of the Southwest were unsuitable for establishment across the 20 modeled years by DDRP, whereas the Maxent and CLIMEX model also predicted unsuitable conditions throughout much of the arid West. Potential model overprediction for the arid West is preferable to underprediction because the tree of heaven, the pest's preferred host, is invasive throughout this region. Additionally, the impacts of aridity on survival of *L. delicatula* are unknown.

For most of northern CONUS, the average date of first egg hatch in 2023 occurred between May and early July (Fig. 5) and the average dates of first adults occurred between late July and September (Fig. 6). Dates for these events were earliest in the Southeast and latest in the Intermountain West. There was insufficient DD accumulation for adults to appear in the coldest areas of CONUS (e.g., northern parts of the Midwest and Northeast), which suggests that *L. delicatula* may be unable to complete its life cycle in these areas. Severe heat stress was predicted for the hottest areas of the Southwest, including in much of western Texas.

5. Future work

The DDRP model for *L. delicatula* should be validated using presence records and phenology observations from the eastern U.S. The climatic suitability model may need to be fine-tuned as more data are gathered on its ability to survive in very hot and cold climates, such as those in the southwestern U.S. and upper midwestern U.S., respectively. Additional records collected from the most climatically extremes parts of the native range, such as in northeastern China (Jilin Province) and in southeastern China, could also help to further refine cold and heat stress parameter values. Predictions of egg hatch and first adults could be compared to those produced by the Spatial Analytic Framework for Advanced Risk Information Systems (SAFARIS), which uses a simple DD lookup table approach and a lower developmental threshold of 8.14 °C vs. 10 °C in DDRP (Takeuchi and Fowler 2018). The SAFARIS model is reportedly accurate to within a few days based on comparisons with field observation dates; however, data to support this finding were not presented (Takeuchi et al. 2023).

6. Conclusions

The DDRP model may be run to test where *L. delicatula* 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. Phenological event maps for egg hatch and appearance of adults may be useful for early detection programs for this pest. An inability for *L. delicatula* to complete development in the coldest areas of CONUS may play a larger role than cold stress in limiting its spread.

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Table 1. Summary of developmental requirements of *L. delicatula* (SLF) in degree-days Celsius (DDCs). The lower threshold is 10 °C. OV = Oviposition.

Stage:	Eggs	Nymphs (Larvae)	Pre-OV Adults (Pupae*)	1st Adults to 1st OV	1st to 50% OV
Stage duration	202	890	630	630	146
Cum. DDs after 1 Jan. (first event)	NA	202	1045	1675	1828

* In the DDRP platform, there are four major stages: egg, larvae, pupae, and adult. We designate nymphal stages L1−L4 as "Larvae" and pre-oviposition adults as "Pupae".

Table 2. DDRP parameter values for *Lycorma delicatula* (SLF).

Parameter	Code	Value
Lower developmental thresholds (°C)		
Egg	eggLDT	10
First and second instar nymph	larvaeLDT	10
Third and fourth instar nymph	pupaeLDT	10
Adult	adultLDT	10
Upper developmental thresholds (°C)		
Egg	eggUDT	35
Larvae	larvaeUDT	35
Pupae	pupaeUDT	35
Adult	adultUDT	35
Stage durations (°C degree-days)		
Egg	eggDD	202
Larvae (L1−L4)	larvaeDD	890
Pupae (pre-oviposition adults)	pupDD	630
Adult (50% oviposition)	adultDD	146
Pest events (°C degree-days)		
OW egg event – suggested label “egg hatch”	OWEventDD	varies
Larva event – suggested label “nymphs halfway developed”	larvaeEventDD	442
Pupa event – suggested label “first adults”	pupaeEventDD	1
Adult event – suggested label “first egg laying”	adultEventDD	1
Egg event – suggested label “diapausing eggs”	eggEventDD	100
Cold stress		
Cold stress temperature threshold (°C)	coldstress_threshold	–16
Cold degree-day (°C) limit when most individuals die	coldstress_units_max1	300
Cold degree-day (°C) limit when all individuals die	coldstress_units_max2	475
Heat stress		
Heat stress temperature threshold (°C)	heatstress_threshold	37
Heat stress degree-day (°C) limit when most individuals die	heatstress_units_max1	115
Heat stress degree-day (°C) limit when all individuals die	heatstress_units_max2	175
Cohorts		
Degree-days (°C) to complete egg development (average)	distro_mean	190
Degree-days (°C) to complete egg development (variation)	distro_var	15,000
Minimum degree-days (°C) to complete egg development	xdist1	135
Maximum degree-days (°C) to complete egg development	xdist2	360
Shape of the distribution	distro_shape	normal
Other		
Order of stages	stgorder	OE, L, P, A, E
Obligate diapause (1 = TRUE)	obligate_diapause	1
Degree day calculation method	calctype	triangle

OE = Overwintered egg, L = nymphal stages (L1−L4), P = pre-oviposition adult, A = adult, E = egg

Table 3. Summary of results for *L. delicatula* (SLF) models that applied different combinations of three cohort parameter values: minimum (xdist1), mean (distro_mean), and maximum (xdist2) degree-days (DDC) to complete egg development. The mean absolute error (MAE), bias (± standard deviation, SD), and number of over-predicted dates (in days) are indicated for each phenological event (first egg hatch and peak egg hatch). Bias was calculated as the average amount by which predicted days of the year (DOYs) are greater than observed DOYs, in which negative values would indicate model underprediction (too early) whereas positive values would indicate overprediction (too late). Parameter set 7 (bold font) was used in the final model.

Set	Event	xdist1	mean	xdist2	MAE	Bias ± SD	No. over-predicted
1	first egg hatch	180	240	400	7.4	1.9 ± 9.1	4
1	peak egg hatch	180	240	400	7.0	2.4 ± 8.4	4
2	first egg hatch	170	240	400	6.4	–0.6 ± 8.0	4
2	peak egg hatch	170	240	400	6.4	1.3 ± 8.1	4
3	first egg hatch	170	230	380	6.4	–0.6 ± 8.0	4
3	peak egg hatch	170	230	380	6.3	0.3 ± 8.1	3
4	first egg hatch	160	220	360	6.0	–2.8 ± 7.6	3
4	peak egg hatch	160	220	360	6.6	–1.1 ± 8.1	3
5	first egg hatch	150	215	360	7.2	–4.8 ± 8.1	3
5	peak egg hatch	150	215	360	6.6	–2.0 ± 7.9	3
6	first egg hatch	140	215	360	7.8	–6.8 ± 7.4	1
6	peak egg hatch	140	215	360	6.7	–3.0 ± 7.9	3
7	**first egg hatch**	**135**	**190**	**360**	**8.0**	**–8.0 ± 7.1**	**0**
7	**peak egg hatch**	**135**	**190**	**360**	**6.7**	**–3.9 ± 7.8**	**2**

Table 4. Comparison of predicted vs. observed dates (day of year, DOY) of first and peak egg hatch for overwintered eggs of *L. delicatula* (SLF) based on the cohort parameter values used in the final model.

Site	State	Event	Date	Obs. DOY	Pred. DOY	Diff (days)	Study
Boyertown	PA	first egg hatch	5/23/2016	144	131	–13	Murman et al. 2020
Boyertown	PA	peak egg hatch	6/5/2016	157	145	–12	Murman et al. 2020
Oley	PA	first egg hatch	5/1/2017	121	120	–1	Liu 2019
Oley	PA	first egg hatch	5/1/2017	121	120	–1	Smyers et al. 2021
Oley	PA	peak egg hatch	5/15/2017	135	139	4	Liu 2019
Oley	PA	peak egg hatch	5/23/2017	143	139	–4	Smyers et al. 2021
Winchester	VA	first egg hatch	4/30/2019	124	116	–8	Smyers et al. 2021
Winchester	PA	first egg hatch	5/1/2019	121	116	–5	Dechaine et al. 2021
Winchester	VA	peak egg hatch	5/7/2019	134	128	–6	Smyers et al. 2021
Winchester	PA	peak egg hatch	5/8/2019	128	128	0	Dechaine et al. 2021
Winchester	VA	first egg hatch	5/10/2019	130	116	–14	Nixon et al. 2020
Kutztown	PA	first egg hatch	5/23/2019	143	123	–20	Leach and Leach 2020
Kutztown	PA	peak egg hatch	6/1/2019	152	137	–15	Leach and Leach 2020
Winchester	PA	first egg hatch	5/7/2020	128	126	–2	Dechaine et al. 2021
Winchester	PA	peak egg hatch	5/16/2020	137	143	6	Dechaine et al. 2021

Figure 1. Maps depicting consecutive cold days and model-predicted cold stress accumulation for *L. delicatula* (SLF) China. Maps of (A) consecutive days of minimum temperatures (T_{min}) below –16 °C based on 20-year climate averages centered on 2008 (1999−2018), (B) annual cold stress accumulation based on 20-year climate averages, and (C) annual cold stress accumulation based on climate data for an extreme year in terms of cold stress accumulation (2001) were used to calibrate moderate and severe cold stress limits in the DDRP model. Presence records are depicted in map A.

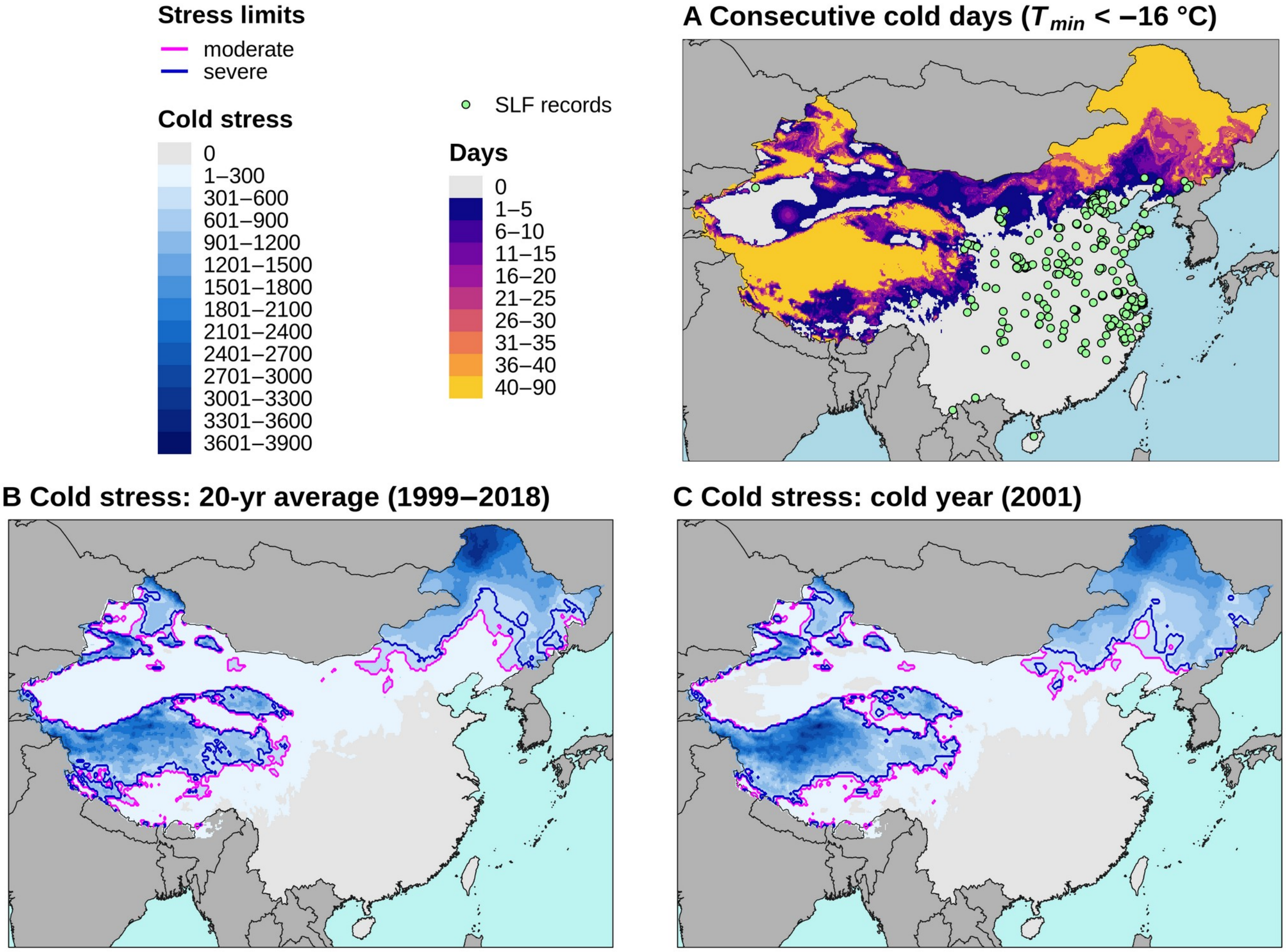
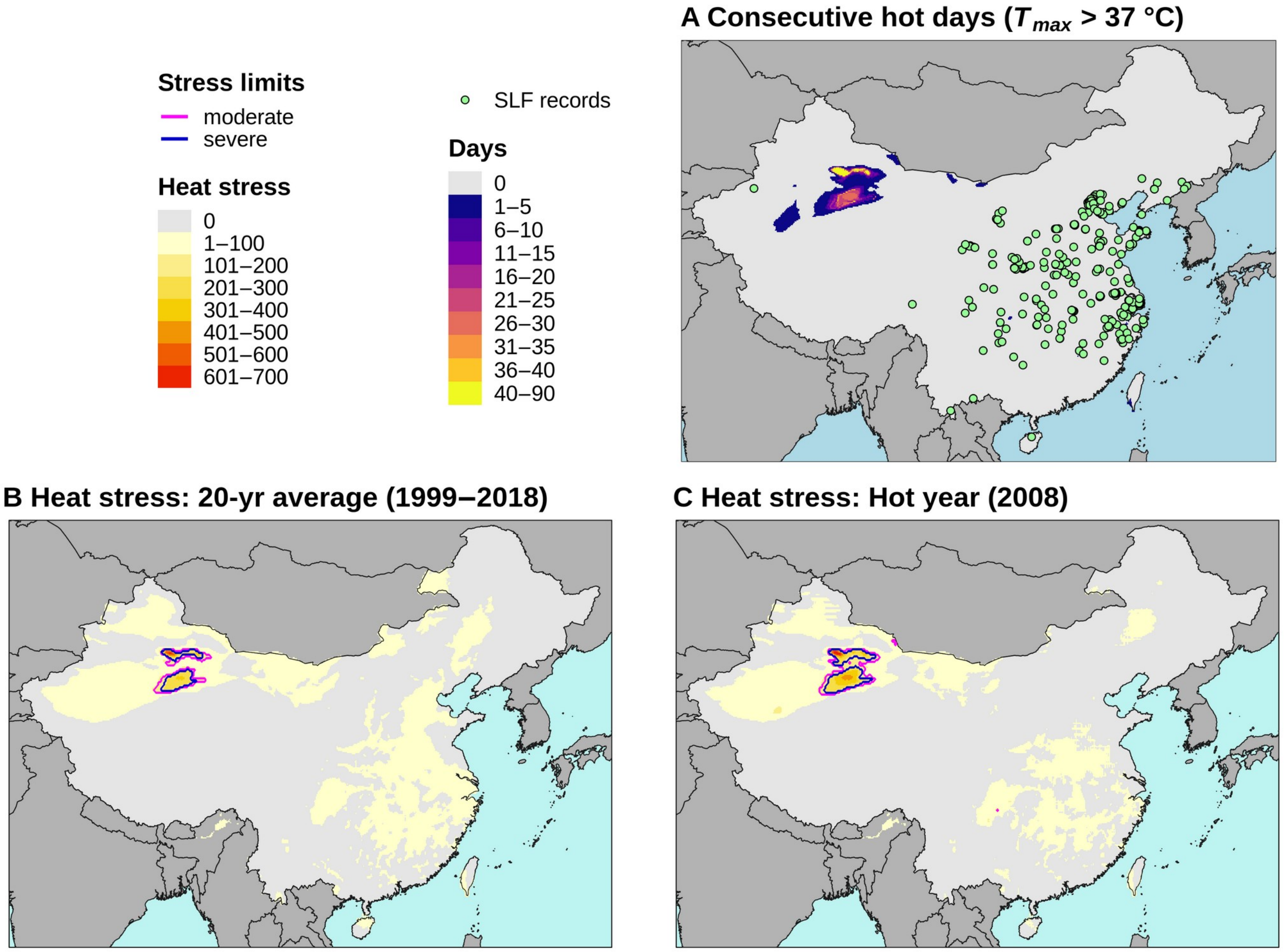


Figure 2. Maps depicting consecutive hot days and model-predicted heat stress accumulation for *L. delicatula* (SLF) in China. Maps of (A) consecutive days of maximum temperatures (T_{max}) above 37 °C based on 20-year climate averages centered on 2008 (1999−2018), (B) annual heat stress accumulation based on 20-year climate averages, and (C) annual heat stress accumulation based on climate data for an extreme year in terms of heat stress accumulation (2008) were used to calibrate moderate and severe heat stress limits in the DDRP model. Presence records are depicted in map A.


A Consecutive hot days (T_{max} > 37 °C)

B Heat stress: 20-yr average (1999–2018)

C Heat stress: Hot year (2008)

Figure 3. The modeled potential distribution for *delicatula* (SLF) in North America (CONUS, southern Canada, and northern Mexico) according to DDRP runs for 20 recent years (2002−2021). Yellow areas were included in the potential distribution for all 20 years, whereas areas with cooler colors were excluded by climate stress for one or more years.

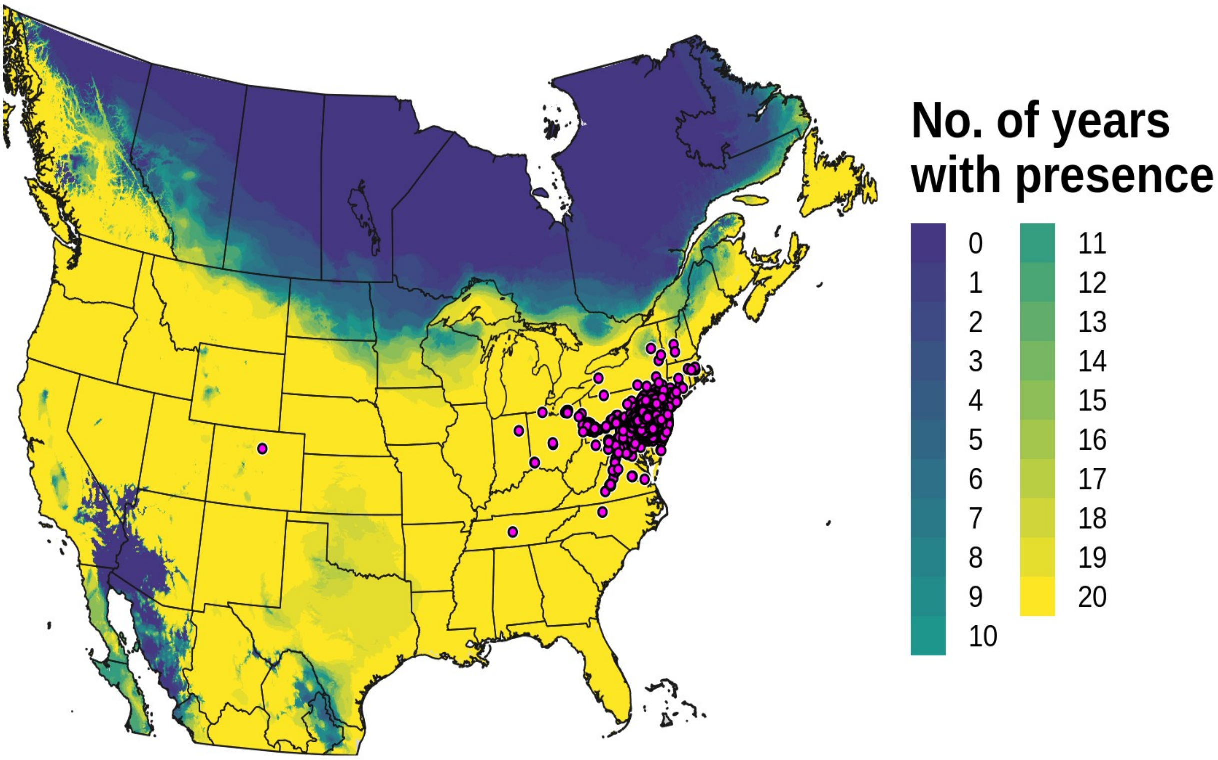


Figure 4. Map depicting the average date of egg hatch of *L. delicatula* (SLF) with severe climate stress exclusion (based on cold and heat stress units) for 2023 produced by DDRP. OW gen. = overwintered generation.

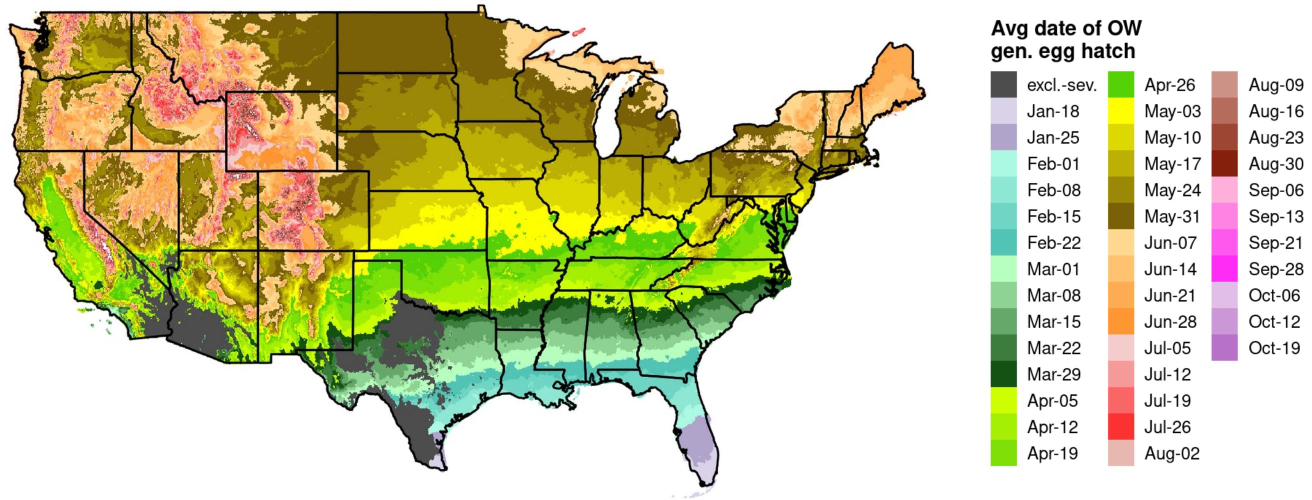


Figure 5. Map depicting the average date of first adults of *L. delicatula* (SLF) with severe climate stress exclusion (based on cold and heat stress units) for 2023 produced by DDRP. OW gen. = overwintered generation.