Pine Tree Lappet Moth

Dendrolimus pini (Lepidoptera: Lasiocampidae)

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 pine tree lappet moth (PTLM), *Dendrolimus pini* (Murayama), was developed using data from available literature and through modeling in CLIMEX v. 4 (Hearne Scientific Software, Melbourne, Australia; Kriticos et al. 2016), Maxent (Phillips et al. 2006), and DDRP (Degree-Days, Risk, and Pest event mapping; under development for uspest.org).

Introduction

Dendrolimus pini is an economically important defoliator of pine and coniferous forests in Europe and Asia. Its primary host is Scots pine (*Pinus sylvestris*) but it can also successfully develop on at least 17 species of pine, as well as *Abies* spp. (fir), *Picea* spp. (spruce), Douglas-fir (*Pseudotsuga menziesii*), hemlock (*Tsuga canadensis*), and common juniper (*Juniperus communis*) (Molet 2012). Approximately 82% of forests in the western U.S. are coniferous, so the potential impact of *D. pini* in this region is significant. The species is widely distributed throughout Europe and Asia and even recorded in North Africa, usually occurring at elevations >200 m (Molet 2012, CABI 2019). The eggs and larvae hidden in bark crevasses may be moved through trade of unprocessed pine logs, although there have been no recorded interceptions of *D. pini* at U.S. ports of entry (Molet 2012).

Phenology model

Objective.—We estimated rates and degree days for of *D. pini* development 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 *D. pini* that is available online at http://uspest.org/wea/Dendrolimus_pini_model.pdf (Coop and Barker 2020). The species typically requires one year to complete its life cycle in southern European countries bordering the Mediterranean and in areas with warm summers (e.g. Poland, Germany and France), but two or even three years may be required in cooler northern European countries

(Hardin and Suazo 2012, Moore et al. 2017). Moore et al. (2017) found that moths from Scotland that were raised under warm laboratory conditions completed egg to adult development in five months, whereas in the field they took two years to complete development (overwintering twice in the larval stage). Thus, generation length does not appear to be genetically fixed.

A summary of phenology model parameters is reported in Table 1. We solved for a common lower threshold of 7.2°C for all four life stages (eggs, larvae, pupae, adults) from examination of multiple studies, as cited herein. Stage degree-day requirements of 181, 1029, 369, and 110 DDs were determined using the x-intercept method based on data sources for the egg stage (Kojima 1933, Schwerdtfeger 1963), the larval stage (Sanderson 1910, who reproduced works by Regener and Ratzeburg; see spreadsheet for original figure and analysis), the pupal stage (Kojima 1933, Winokur 1991), and adults (teneral and *ca.* 40% oviposition time; works cited in Hardin and Suazo 2012). The generation time was estimated as 1689 DDC, which is the sum of these stage durations. We set the upper developmental threshold to 30°C based on an earlier NAPPFAST model (Hardin and Suazo 2012), and by evidence from the above studies that demonstrated reduced or no development at 31.5°C for the egg stage and 32°C for the pupal stage. In addition, Frydrychewicz (1934) found that 100% mortality of the first larval instar occurs at temperatures above 30°C.

Emergence parameters.—Overwintering in *D. pini* occurs in the larval or prepupal stage (Molet 2012, Moore et al. 2017). We assumed seven cohorts begin pupating in the spring according to a normal distribution. Field monitoring data on the spring activity of larvae and pupae are lacking, so we estimated a distribution of pupation times based on monitoring data for adult flight. There was evidence for two types of overwintering based on flight patterns. In more northern regions of Europe, overwintering was by prepupae that pupated as soon as spring warm-up commenced (Ostrauskas and Ivinskis 2011, Björkman et al. 2013). In mid- and southern regions of Europe, which more closely match the climate of CONUS, mid or late instar larvae were more likely to overwinter, wherein further larval feeding and development happens upon spring warm-up (Priesner et al. 1984). This resulted in two versions of the model at least for spring flight. First spring flight ranged from 367 to 574 DDC (colder vs. warmer regions), and peak adult flight was 973 DDC (warmer), which corresponded to end of flight for colder regions. For warmer regions, end of flight was 1372 DDC. Since we are building a single DDRP model for CONUS, we will adopt the warmer climate results for PTLM. Other events such as first egg hatch were calculated from the above results.

Climate suitability model

<u>Background and Objective</u>

Two risk assessments for *D. pini* in the contiguous U.S. (CONUS) have been conducted. The USDA-APHIS-PPQ-CPHST (Molet 2012) generated a risk map based on the density of potential host trees, whereas Hardin and Suazo (2012) presented a NAPPFAST risk map for establishment potential based on climatic suitability (Fig. 1). With the exception of the NAPPFAST model, there are no published climate suitability modeling studies for *D. pini*, and little is known about its climatic tolerances (e.g. cold stress, heat stress, dry stress, and moisture stress thresholds).

Our objective was to parameterize a climate suitability model for *D. pini* in CLIMEX and DDRP. These two programs use a similar process-based approach to estimate climate suitability and many of their model products are directly comparable. We also generated a model using a correlative approach in Maxent version 3.4.1 (Accessed from https://biodiversityinformatics.amnh.org/open_source/maxent/ on 2020-3-11) to provide an independent perspective into climate suitability.

CLIMEX and Maxent analyses

Localities.—We used locality 3,800 records from GBIF.org (14 March 2020; GBIF Occurrence Download https://doi.org/10.15468/dl.shltdk) to fit a CLIMEX and Maxent model for *D. pini*. Maxent assumes that all locations on the landscape are equally likely to be sampled; however, we found a large amount of spatial bias in the locality dataset, particularly in western and northern Europe compared to the rest of Eurasia. We therefore subsampled locality data using the 'spatEco' package in R (R vers. 3.61) as follows. First, a single locality record was retained if several localities occurred within a 20 km radius ("subsample.distance"). Next, we applied a spatial intensity function ("pp.subsample") to account for regional biases in sampling, which resulted in selection of 600 localities.

CLIMEX model.—The parameters used for the CLIMEX model are reported in Table 2. We set the cold stress threshold to –15°C because weather records indicate that a city close to the northernmost locality for *D. pini* (Kuusamo, Finland) has an average low-temperature of −18°C during the coldest month of year (January). We assumed that *D. pini* would begin experiencing heat stress at 31°C, which is 1°C higher than the upper developmental threshold.

Predictions of climate suitability in CLIMEX are based in part on population growth for a single year, which is an issue for *D. pini* because populations at northern latitudes have a 2–3 year life cycle. When we set the generation length parameter (PDD) in CLIMEX to 1689 DDC, the model predicted unsuitable conditions throughout northern Europe because population growth for a single year was zero. We therefore set the PDD parameter to 515 DDC [50% of the estimated larval duration (1029 DDC)] to approximate the degree-days required for the species to reach the later larval instar stages at northern latitudes so it may overwinter a second time. Thus, reaching the PDD value at a site signifies population persistence rather than growth.

Maxent model.—Climate data for the Maxent model included 19 Bioclim variables from the CliMond database (https://www.climond.org/BioclimRegistry.aspx#Table1), which are derived from monthly averages of daily minimum and maximum temperatures and monthly precipitation for 1961−1990. We estimated the first two principal components (PCs) of Bioclim variables with a standardized PCA in the 'RStoolbox' in R, which captured 78% of the variability in the full dataset. PC data are often used to estimate climate suitability models in Maxent to avoid model over-fitting due to correlations among variables (Kriticos et al. 2014).

Maxent models were trained using PC data that were cropped to the extent (bounding box) of the native range localities. We created 50 replicate models for each variable using a random 80% subset of localities to train the model and 20% reserved for testing using the area under the receiver operating curve (AUC) statistic for each replicate. Model replicates were then projected at the scale of CONUS using the same variables. Other settings were left as default. The native range Maxent models performed adequately based on AUC values (average AUC_{test} over 50 replicate runs was 0.84 ± 0.01).

DDRP model.—A summary of DDRP parameters used for climate suitability modeling of *E. pini* 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 and Maxent. We adjusted the cold and heat stress thresholds and limits in accordance with CLIMEX products for cold stress, heat stress, and the ecoclimatic index (EI). For example, we set the DDRP moderate cold stress limit (max1) to 380 to match the limit where CLIMEX predicted that cold stress was contributing to low suitability in the native range (at *ca.* 27 cold stress units). Areas where DDRP predicted severe stress exclusion were unsuitable according to CLIMEX (EI = 0), and areas under moderate stress exclusion had low suitability (0 < EI < 20; Fig. 2).

Results

Native range.—The CLIMEX and Maxent models for *E. pini* in the native range predicted suitable conditions at most localities where the species has been documented (Figs. 2a and 2b). According to CLIMEX, all localities except for those at the northern range edge fell within areas that had EI > 20, so we considered areas with an EI > 20 to be part of the potential distribution. According to Maxent, the majority of localities (575/600) were in areas with a log suitability score of at least 0.15.

CONUS.—All three modeling platforms predicted suitable conditions throughout eastern CONUS, except that CLIMEX and DDRP excluded most of the Gulf Coast region from the potential distribution (Fig. 2). In the West, Maxent predicted suitable conditions only in the Pacific Northwest, whereas CLIMEX and DDRP included most regions of the West in the potential distribution except for parts of the Southwest, Great Basin, and Great Plains.

According to CLIMEX and DDRP, cold stress excluded *E. pini* only from the coldest parts of the upper Midwest (e.g. northern Minnesota; Fig. 2c, Fig. 3). Conversely, heat stress was the major determinant of the potential distribution in CONUS (Fig. 4), as it excluded the species from most of the Southwest, Gulf Coast states, and lower Midwest (Fig. 2c). In general, the CLIMEX and DDRP climate suitability models were consistent with the previously published NAPPFAST model for the species (Fig. 1).

Suggested applications

The DDRP model may be run to test where *D. pini* 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 emergence for one or more generations to guide APHIS supported Cooperative Agricultural Pest Survey (CAPS) programs. We provide two example maps using 2012 PRISM data (the hottest year on record for the conterminous US (CONUS) showing (a) the date of first egg laying by females with severe climate stress exclusions (Fig. 5), and (b) potential voltinism (no. of gens.; Fig. 6).

Improvements needed

Additional reports on adult flight patterns would help refine estimates of spring emergence for different climate regions of Europe, and for corresponding regions in North America. Some of the stage development data available for analysis is surprisingly old (e.g. 1910 for the larval stage). The CLIMEX model is based on limited amounts of data on the climatic tolerances of *D.*

pini. In particular, additional information on the moisture stress thresholds of the species would help to further calibrate the model.

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Table 1. DDRP parameter values for *Dendrolimus pini*.

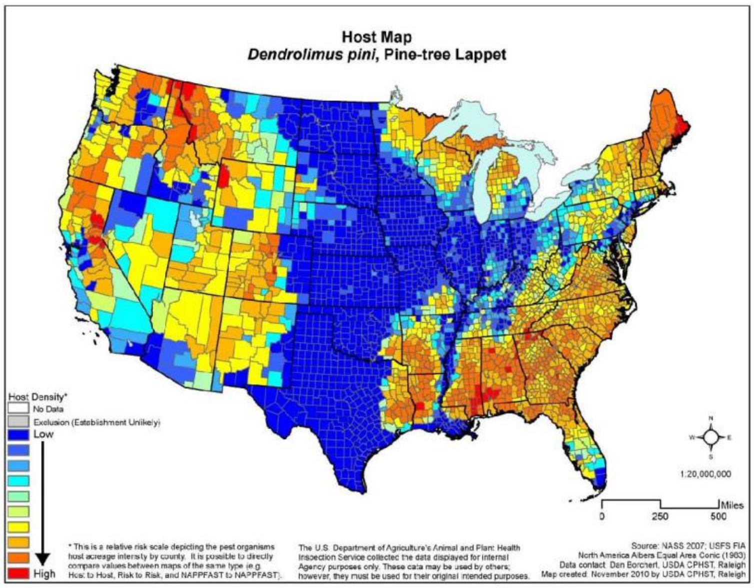
Parameter	Code	Value
Lower developmental thresholds (°C)		
Egg	eggLDT	7.2
Larvae	larvaeLDT	7.2
Pupae	pupaeLDT	7.2
Adult	adultLDT	7.2
Upper developmental thresholds (°C)		
Egg	eggUDT	30.0
Larvae	larvaeUDT	30.0
Pupae	pupaeUDT	30.0
Adult	adultUDT	30.0
Stage durations (°C degree-days)		
Egg	eggDD	181
Larvae	larvaeDD	1029
Pupae	pupDD	369
Adult	adultDD	110
Pest events (°C degree-days)		
Egg event (first egg-hatch)	eggEventDD	180
Larval event (mid-larval peak)	larvaeEventDD	576
Pupal event (first adult emergence)	pupaeEventDD	365
Adult event (first egg-laying)	adultEventDD	70
Cold stress		
Cold stress temperature threshold (°C)	coldstress_threshold	-15
Cold degree-day (°C) limit when most individuals die	coldstress_units_max1	380
Cold degree-day (°C) limit when all individuals die	coldstress_units_max2	1000
Heat stress		
Heat stress temperature threshold (°C)	heatstress_threshold	30
Heat stress degree-day (°C) limit when most individuals die	heatstress_units_max1	190
Heat stress degree-day (°C) limit when all individuals die	heatstress_units_max2	275
Cohorts		
Avg. degree-days (°C) to OW pupation	distro_mean	222
Var. in degree-days (°C) to OW pupation	distro_var	5000
Minimum degree-days (°C) to OW pupation	xdist1	0
Maximum degree-days (°C) to OW pupation	xdist2	441
Shape of the distribution of degree-days (°C) to OW pupation	distro_shape	normal

Table 2. Parameter values used in the CLIMEX model for *Dendrolimus pini*.

CLIMEX parameter	Code	Value
Temperature		
Lower temperature threshold (°C)	DV0	7.2
Lower optimal temperature (°C)	DV1	13
Upper optimal temperature (°C)	DV2	23
Upper temperature threshold (°C)	DV3	30
Degree-days per generation (°C days)	PDD	515
Moisture		
Lower soil moisture threshold	SM0	0.1
Lower optimal soil moisture	SM1	0.3
Upper optimal soil moisture	SM2	1.7
Upper soil moisture threshold	SM3	2.5
Cold stress		
Cold stress temperature threshold (°C)	TTCS	–15
Cold stress temperature rate (week^{-1})	THCS	–0.001
Heat stress		
Heat stress temperature threshold (°C)	TTHS	31
Heat stress temperature rate (week^{-1})	THHS	0.01
Dry stress		
Dry stress threshold	SMDS	0.1
Dry stress rate (week^{-1})	HDS	–0.01
Wet stress		
Wet stress threshold	SMWS	2.5
Wet stress rate (week^{-1})	HWS	0.0003

Fig. 1. Previously published risk maps for *Dendrolimus pini* (PTLM) in CONUS. (a) The risk map produced by USDA-APHIS-PPQ-CPHST (Molet 2012) is based on the relative density of susceptible host trees (scale of 1 to 10; warm colors indicate higher risk). (b) The NAPPFAST risk map for establishment potential is based on climatic suitability (Hardin and Suazo 2012).

(a)



(b)

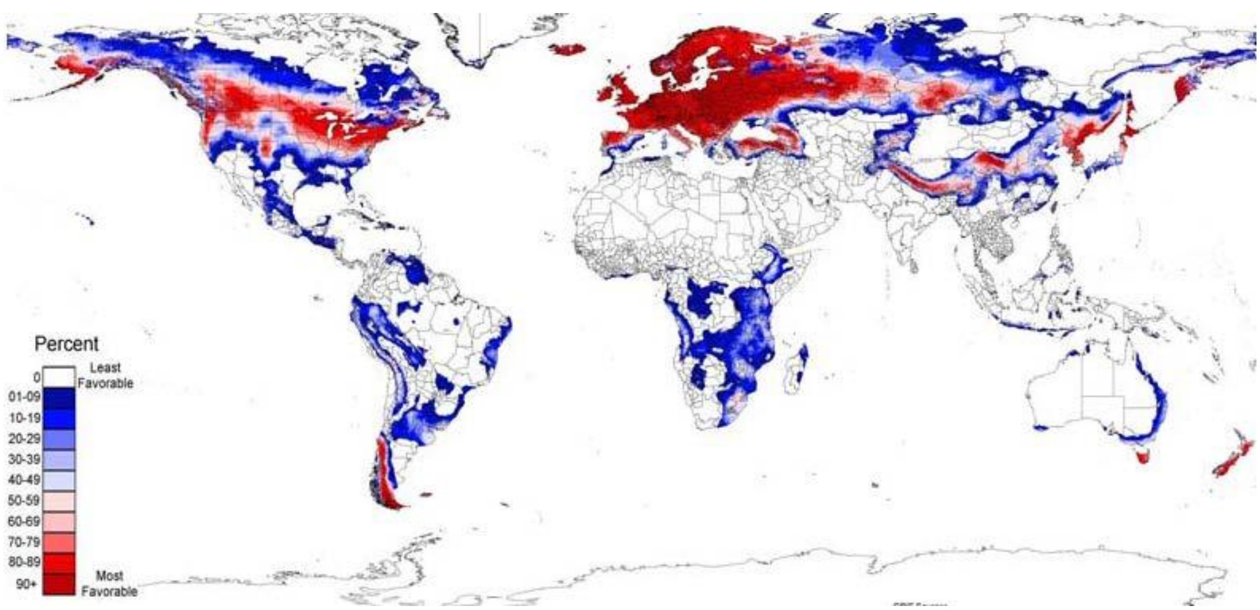


Fig. 2. Comparison of climate suitability models for *Dendrolimus pini* (PTLM) in the native range and CONUS generated by (a) CLIMEX, (c) Maxent, and (d) DDRP. Reference climate data for DDRP were from 1961–1990 Normals.

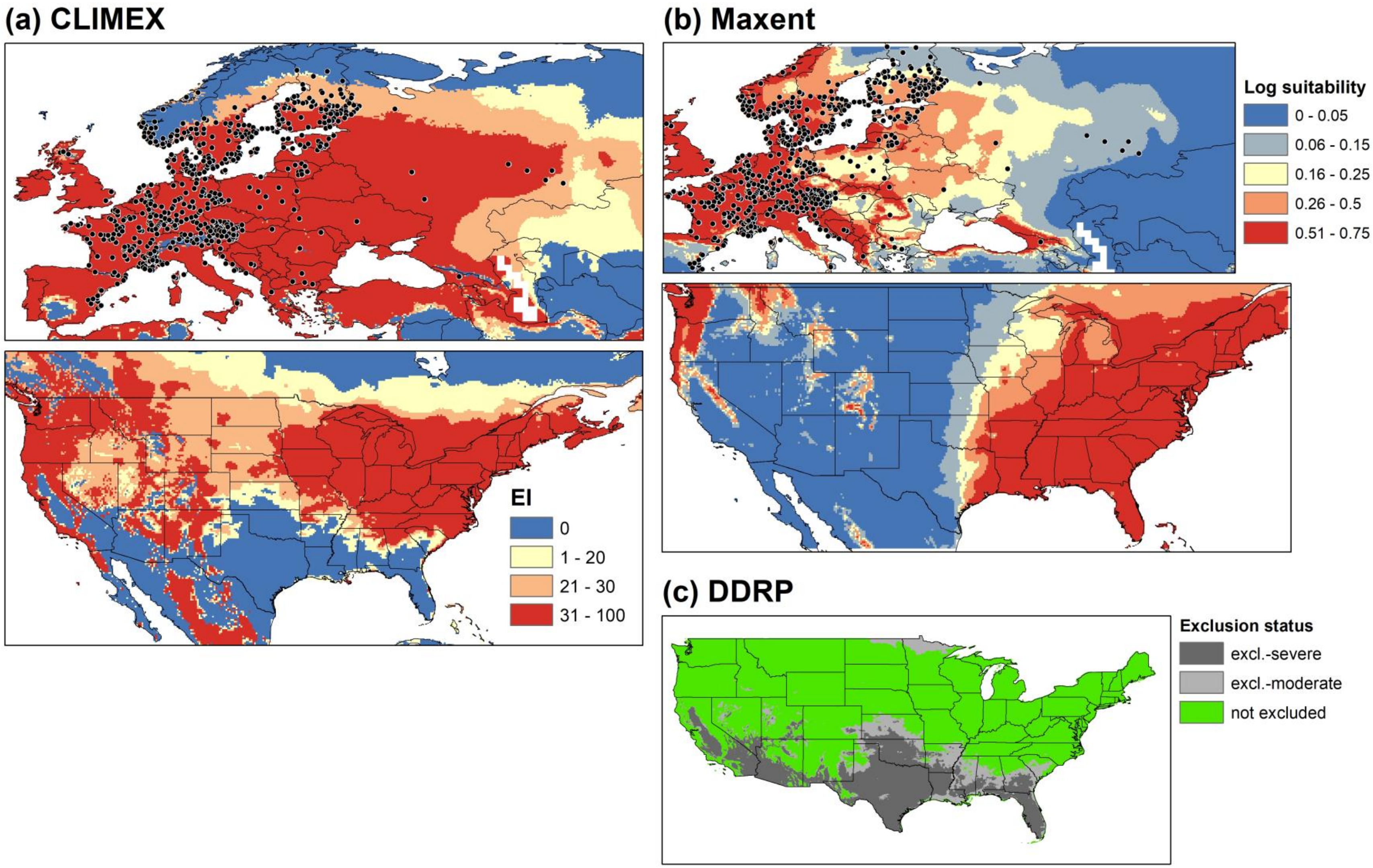


Fig. 3. Maps of cold stress units for *Dendrolimus pini* (PTLM) produced by (a) CLIMEX and (b) DDRP (cold stress temperature threshold = –15ºC). Cold stress units have been scaled from 0 to 100. Reference climate data for DDRP were from 1961–1990 Normals (matched to available CLIMEX data). The pink line in (b) depicts the cold stress unit limit 1 (380 CSUs).

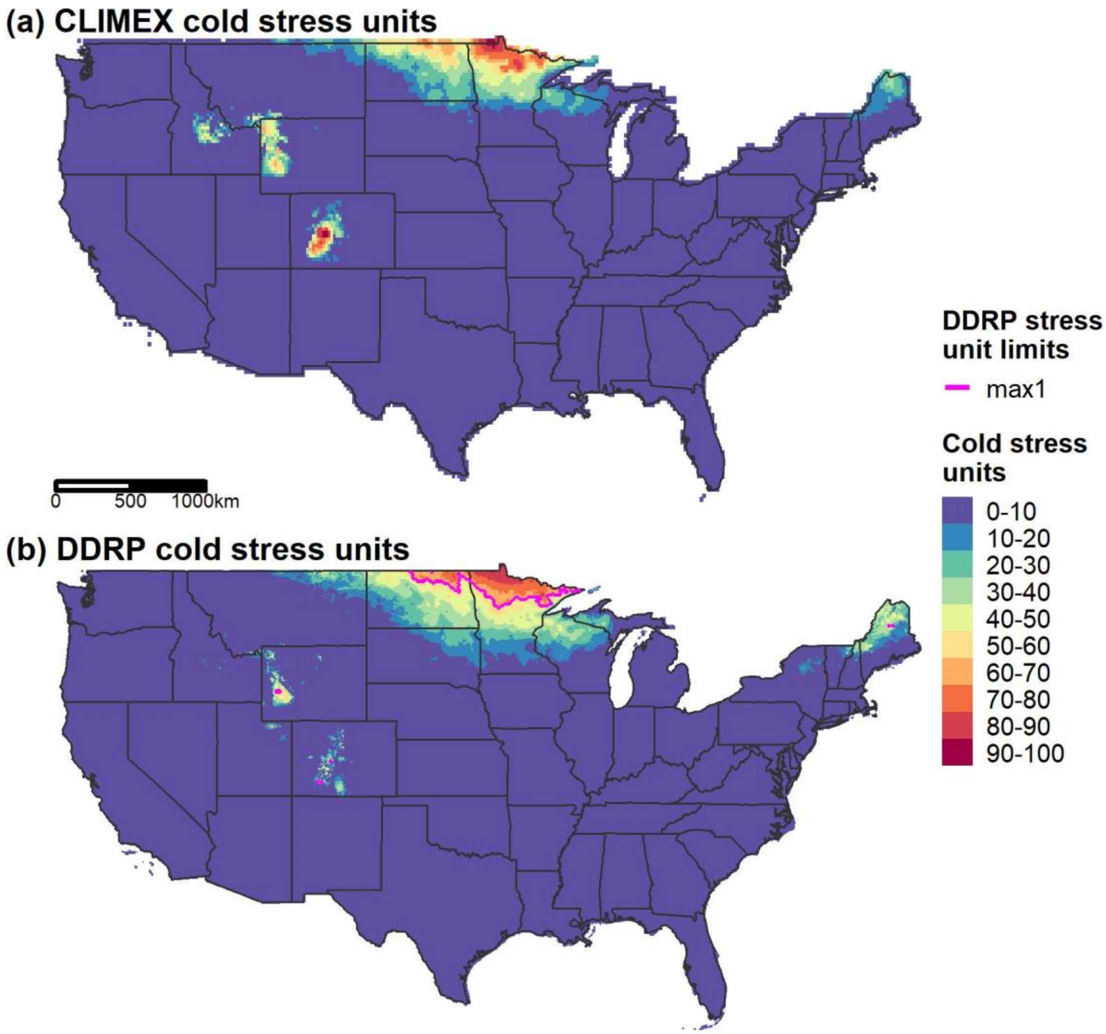


Fig. 4. Maps of heat stress units for *Dendrolimus pini* (PTLM) produced by (a) CLIMEX and (b) DDRP (heat stress temperature threshold = 30ºC). Heat stress units have been scaled from 0 to 100. Reference climate data for DDRP were from 1961–1990 Normals (matched to available CLIMEX data). The pink and black lines in (b) depict the heat stress unit limits 1 and 2 (190 and 275 CSUs, respectively).

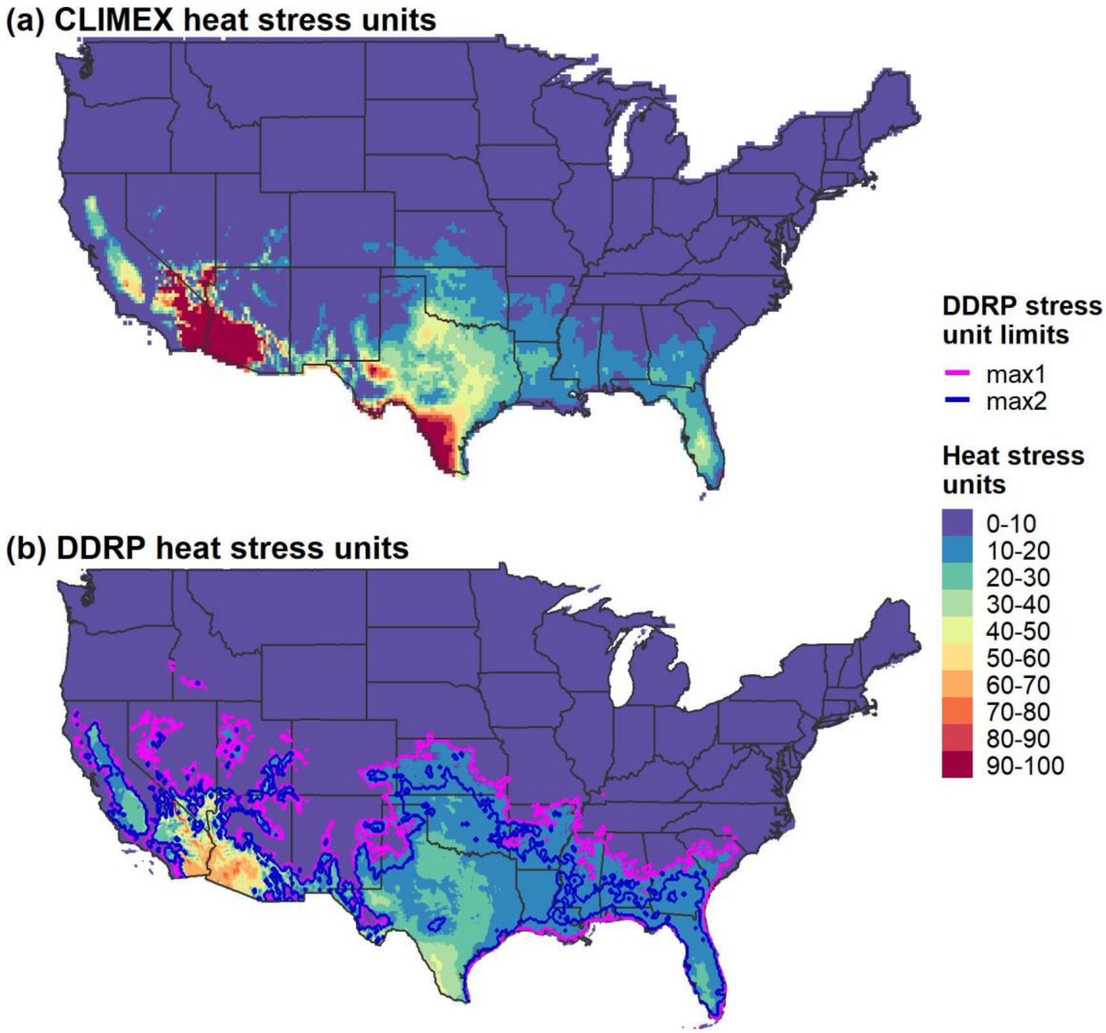


Fig. 5. Map depicting the average date of first egg laying of the overwintered generation of *Dendrolimus pini* (PTLM) with severe climate stress exclusion (based on cold and heat stress units) for 2012 produced by DDRP.

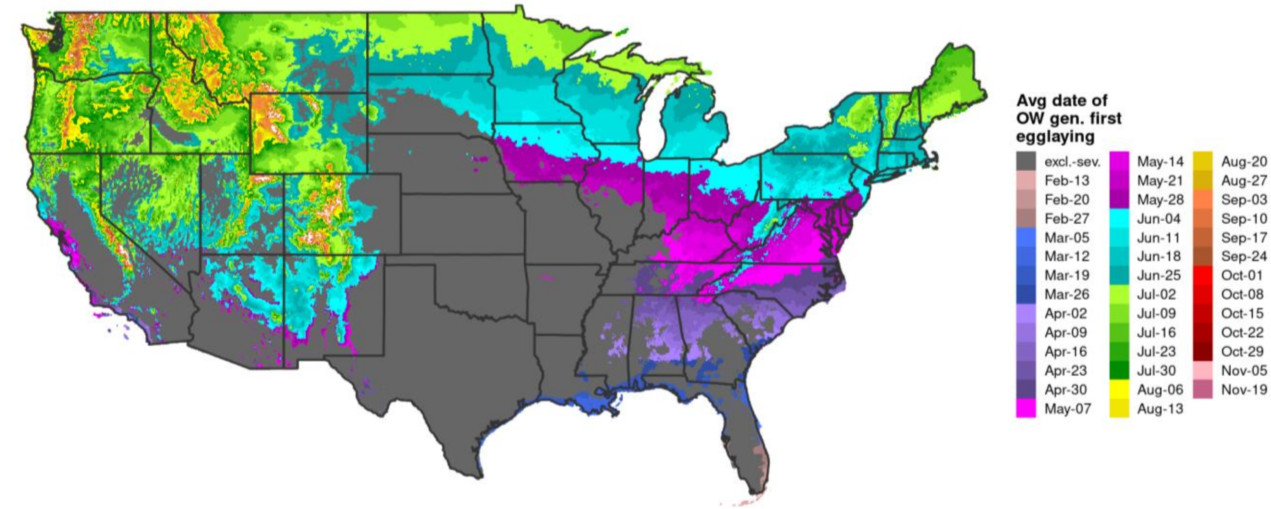


Fig. 6. Map showing the voltinism (number of generations) of *Dendrolimus pini* (PTLM) with severe climate stress exclusion (based on cold and heat stress units) for 2012 produced by DDRP.