Phenology/Degree-Day and Climate Suitability Model Analysis – Vers. 2, Feb. 26, 2020

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Japanese Pine Sawyer Beetle ***Monochamus alternatus*** **(Hope)** **[Coleoptera: Cerambycidae]**

Hosts: *Pinus* spp. (pine), fir, cedar, larch, spruce **Damage: wood boring beetle that also vectors pinewood nematode**

Goal: Develop a phenology model and temperature-based climate suitability model using available literature and weather data analysis

Steven Valley, Oregon Department of Agriculture, Bugwood.org

All other images from https://wiki.bugwood.org/HPIPM:Pine_Sawyer

Sources and Data: **(Note significant data used in final model highlighted in Salmon color)**

1. NAPPFAST Model Documentation June 2008

Aphis 1; generic Dds; Base Temp. 13C 981 DD total

Egg 85, larvae 369, pupae 333.3, adult 193 based on Enda 1975, Okuda 1973, Park et al 1992, and Rutherford et al 1987

Exclusion: Aphis 1 Generic 1; X < A where Avg temp -25C
Prob of 1-3 gens
Exclus: Prob of unfav temps -25C

2. Park, C.G, D.S. Kim, S.M. Lee, Y.S. Moon, Y.J. Chung, and D.S. Kim. 2014. A forecasting model for the adult emergence of overwintered *Monochamus alternatus* (Coleoptera: Cerambycidae) larvae based on degree-days in Korea. Appl Entomol. Zool: 49:35-42.

Selected Jan 1 start date; 11.9C as best low temp threshold

3 types of models for when they OW as: 4th instar (advance mode), 3rd instar (delay mode), regular mode (blend of 3rd and 4th instars

DD reqs:	5% emerg	10% emerg	25% emerg	50% emerg	75% emerg	90% emerg	
preliminary (ign	210	240	321	416	510	591	
advance year	200	230	260	340	405	584	
Regular year	204	270	350	420	500	600	
Delay year	245	310	410	500	580	635	
avg of adv+reg	202	250	305	380	452.5	592	
avg of adv+reg	196	243	297	370	440	576	Convert 11.9 to 12.2 Tlower

3. Kobayashi F., A. Yamane, and T. Ikeda. 1984. The Japanese pine sawyerbeetle as the vector of pine wilt disease.

Annu. Rev. Entomol. 29:115–135

Tlow=11.9 or 12.5C
DD to 50% emerge: 540 (11.9base) or 500 (12.5base)
(and see below)

4. Togashi, K. 1989. Development of Monochamus alternatus Hope (Coleoptera: Cerambycidae) in relation to oviposition time. Jap. J. Appl. Entomol. Zool. 33:1-8.

Ovip sometimes as late as Oct in central Japan

5. Togashi K. and H. Magira. 1981. Age-specific survival rate and fecundity of the adult Japanese pine sawyer *Monochamus alternatus* Hope (Coleoptera: Cerambycidae), at different emergence times. App. Ent. Zool. 16: 351-361.

Avg life-span of adults is 7 weeks in outdoor cages in central Japan

6. Song, S.H., L.Q. Zang, H.H. Huang, and X.M. Cui. 1991. Preliminary study of biology of *Monochamus alternatus* Hope. Forest Sci. and Technol. 6:9-13.

Avg life-span of adults is 12-13 weeks in outdoor cages in Guangdong
Bivoltine, adults first emerge Apr-May, 1st gen July-Aug
If trivoltine emerge Mar-Apr, June-July, mid-Oct-early Nov

See detailed analysis (separate Tab in spreadsheet) for details:
Estimated first emerge (bivoltine): ca 360 DDC (12.2 Tlow)
Estimated first emerge (trivoltine): ca 200 DDC (12.2 Tlow)
Notes: trivoltine assumption best matches #2 Park et al. 2014 above

7. Misc notes from CABI data sheet: http://www.cabi.org/isc/datasheet/34719
Wang 1988.

Univoltine in Jiansu China, bi or trivoltine in Guangdong (Song et al 1991)

Adults emerge reproductively immature; feed on bark of pine twigs; males take at least 5 days before mating; femailes take at least 3 weeks before able to oviposit; large variation in Pre-OV period

Immature adults disperse in random direction; attracted to extracts from healthy Pinus tree trunks.
Mature adults attracted by monoterpenes and ethanol emitted from damaged/dying Pinus trees.
Not a strong flyer, fly more while immature; found to move 7 to 40 m per week in Pinus thunbergii stands (Togashi 1990)
Known to fly up to 1-2 km (Fujioka 1993)
Adults are nocturnal (Nishimura 1973)

Age-specific fecundity curve is unimodal under outdoor conditions; Mean fecundity was 86 in Ishikawa (Togashi and Magira 1981)
Mean fecundity was 33 in Nara (Shibata 1987); 157, 78, and 24 for early, mid, and late emerged females (Togashi and Magira 1981)
Mean fecundity was 88 in Jiangsu China (Wang, 1988)
Lifetime fecundity ranges from 0 to 343

Summary of Degree-Day Estimates

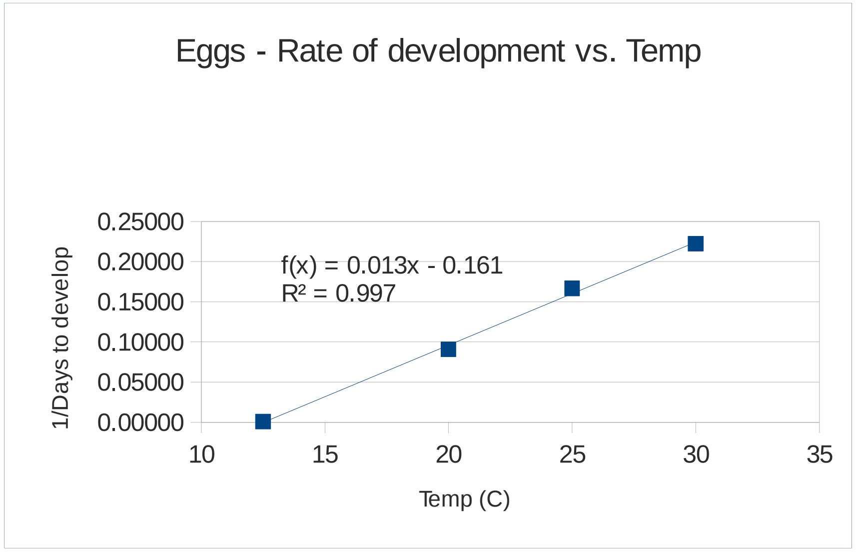
Eggs

DD reqs: C	Tlow: C	Notes	References
85.5	12.9		Okuda 1973
		10 to 12 days at 20 C, 5-7 days at 25 C, and 4-5 days at 30 C	rev. by Kobiashi et al. 1984

x-intercept method using Okuda 1973 data:

Temp	Rate (Eggs)	days
12.5	0.00100	999
20	0.09091	11
25	0.16667	6
30	0.22222	4.5

slope	0.01284
intercept	-0.16066
R2	0.99730
1/Slope	77.9
X-intercept	12.5



DD reqs: C	Tlow: C	Notes	References
65	12.7		rev. by Kobiashi et al. 1984
89	13		rev. by Kobiashi et al. 1984
80	12.5	Based on all of the above	
83	12.2	Estimated conversion from 80 at 12.5 (see Appendix 1)	

Larvae

feed on inner bark to develop	
3rd and 4th instars excavate a tunnel in wood & enter when danger occurs	
central Japan OW at 1st to 4th instar larvae	Togashi 1989
diapause terminated by cold (chilling units) in winter; by mid-Feb in the field	Togashi 1991

DD reqs: C	Tlow: C	Notes	References
333.3	12.6	for post-diapause larvae to pupate	Enda 1975
526.3	11.9	for post-diapause larvae to adults	Enda 1975
625	12.5	full non-diapause larval development	rev. by Kobiashi et al. 1984 (Okuda 1973)
647	12.2	Estimated conversion from 625 at 12.5 (see Appendix 1)	
540	12.5	time to 50% adult emerg in spring from OW larvae (maybe warmer climate)	rev. by Kobiashi et al. 1984 (Okuda 1973)

Pupae	12-13 days at 25 C	Yamane 1974

X-intercept method using Yamane 1974 data:

Temp	Rate (pupae)	days
12.2	0.00010	9999
25	0.08000	12.5

slope	0.00624
intercept	-0.07605
1/slope	160.2
X-intercept	12.2

DD reqs: C	Tlow: C		
160	12.5	Estim. From above data point by Yamane 1974	
166	12.2	Estimated conversion from 160 at 12.5 (see Appendix 1)	
		diapause obligate in Japan and facultative in Taiwan	Okuda 1969 & Enda and Kitajima 1990
		in nature 17-19 days	rev. by Kobiashi et al. 1984
187	10.6	Refs 13,17 in review article	rev. by Kobiashi et al. 1984

Adult Pre-OV	mating begins 10 days after emergence; eggs not yet mature in females upon emerge	rev. by Kobiashi et al. 1984

DD reqs: C	Tlow: C	
100	12.5	rough estim. From above assuming emerge mid-late march
103	12.2	Estimated conversion from 100 at 12.5 (see Appendix 1)

Adult OV	peak OV at 45 days after emerg.	rev. by Kobiashi et al. 1984
	OV period ranges from 20 to 30 days with threshold of 21.3 C	rev. by Kobiashi et al. 1984 (59 & 184)

X-intercept method using above data:

Temp	Rate (PreOV)	days
21	0.00100	999
24	0.02273	44
28	0.04167	24
30	0.05000	20

slope	0.00537
intercept	0.10939
1/slope	186.3

X-intercept method using above data; forced through 12.5 C Tlow

Temp	Rate (PreOV)	days
12.5	0.00100	999
24	0.02273	44
28	0.04167	24
30	0.05000	20

slope	0.00271
intercept	0.03776
1/slope	368.5

(this is coarse and could be improved
with access to refs such as 1984,
Takizawa 1980)

Therefore a rough estimate of OV period is 368 DD (12.5 Tlow)
50% OV period would be 184 DD (12.5 Tlow), estim. 35% OV would be 100 DD (rough estim.)

OV for gens

DD reqs: C	Tlow: C		
100	12.5	value to use to estimate generation time	
103	12.2	Estimated conversion from 100 at 12.5 (see Appendix 1)	

Adults	adult flight ceases below 18 C	rev. by Kobiashi et al. 1984
	movement (dispersal) ranges from 800m to 3.3 km	rev. by Kobiashi et al. 1984

Gen Time

DD reqs: C	Tlow: C		
		Normal: 1 gen/yr; cooler climate: 1 gen/2 yrs;	rev. by Kobiashi et al. 1984
1065	12.5	Estimated from above (Egg+Larvae+Pupae+PreOV+35%OV); mainly Okuda 1973	
981	13	Nappfast model	
1133	11.9	Estimated conversion from 1065 at 12.5 (see Appendix 1)	
1102	12.2	Estimated conversion from 1065 at 12.5 (see Appendix 1)	

OW to 5% (first) emerge

DD reqs: C	Tlow: C		
360	12.2	Assuming Bivoltine; China near Hong Kong (warm climate)	based on Song et al 1991; see analysis
200	12.2	Assuming Trivoltine; China near Hong Kong (warm climate)	based on Song et al 1991; see analysis
196	12.2	Estimated conversion from 202 at 11.9 (see Appendix 1)	Park et al 2014 (Korea); table above

Conclusion: Use 200 DDC (12.2) as first emergence from two sources

OW to 50% emerge

DD reqs: C	Tlow: C		
500	11.9	time to 50% adult emerg in spring from OW larvae (maybe cooler climate)	rev. by Kobiashi et al. 1984
540	12.5	time to 50% adult emerg in spring from OW larvae (maybe warmer climate)	rev. by Kobiashi et al. 1984 (Okuda 1973)
380	11.9		Park et al 2014 (Korea)
370	12.2	Estimated conversion from 380 at 11.9 (see Appendix 1)	

OW to 90% emerge

DD reqs: C	Tlow: C		
592	11.9		Park et al 2014 (Korea)
576	12.2	Estimated conversion from 592 at 11.9 (see Appendix 1)	

Summary of Phenology Model for *Monochamus alternatus* (using a common lower threshold of 12.2 C)

Start Date: January 1st
Calc Method: Single Sine

	Deg. C	Deg. F	
Tlower	12.2	54.0	
Tupper	35	95	(nominal value based on climate suitability studies see below)

Primary Events	**DD C**	**DD F**
Egg	83	149
Larvae	647	1164
Pupae	166	298
Egg to Adult	895	1611
Pre-OV+35% OV	207	373
Generation Time	1102	1983

Events Table		
OW to 5% (first) emerge	200	360
OW to 50% emerge	370	666
OW to 90% emerge	576	1037
2nd Generation 5% emerge	1302	2344
2nd Generation 50% emerge	1472	2650
2nd Generation 90% emerge	1678	3020
3rd Generation 5% emerge	2404	4327
Full generation time (35% OV to 35% OV)	1102	1984

Note: only adult OV indicated to have a significantly higher Tlower = 21.3 C;

Appendix – Estimated conversion from 12.5 C 1065DD → 11.9 and to 12.2 C (=54F)

Strt Apr 1 Method used: 3 yrs x 4 locations where insect is likely to survive; calc Date of 1065 Dds @ 12.5; change Tlow to find Dds for same date

Code	AP525	AP525	AP525	KBGD	KBGD	KBGD	KPBF	KPBF	KPBF	NNAG1	NNAG1	NNAG1	Average
Loc	Anderson CA	Anderson CA	Anderson CA	Borger CO	Borger CO	Borger CO	Pine Bluff AR	Pine Bluff AR	Pine Bluff AR	Newnan GA	Newnan GA	Newnan GA	
Date 1065	07/23/15	07/28/14	07/23/13	07/25/15	07/20/14	07/16/13	07/13/15	07/22/14	07/20/13	07/12/15	07/22/14	07/26/13	
Dds @ 11.9	1128	1145	1135	1133	1139	1120	1143	1128	1127	1128	1133	1140	1133
Dds @ 12.2	1101	1112	1101	1101	1109	1092	1112	1097	1097	1097	1100	1107	1102

Climate suitability model

8. Ma, R-Y, S-G Hao, W-N Kong, J-H Sun, and L. Kang. 2006. Cold hardiness as a factor for assessing the potential distribution of the Japanese pine sawyer. Annals of Forest Science. 63:449-456.

- Studied the effects of low temps on survival of eggs, overwintering 4-5th instar larvae, pupae and adults
- Exposed eggs, pupa and adult individuals from -25 to 5C with 5C increments for 1/16 d; larvae were exposed to 7 low temps (from -25 to 5C with 5C increments)
- They estimated the potential distribution based on -10 and -4C isotherms of avg. Jan mean air temperature in China from 1961-1990, where:
  1) non-survial regions = below -10C isotherm
  2) dispersal regions = between -10 and -4C isotherms
  3) suitable survival regions = above -4C isotherm

- NOTE: their "suitable distribution region" is farther north than the CLIMEX model of Kim et al. (2016) [source 8]
- Mortality rates did not significantly differ at 0, 5, and 25C, which suggests that cold stress doesn't affect the species much above 0C

Figure 3. Mortality (mean plus/minus S.E.) of dfferent stages after exposure to low temps for 1/16 d

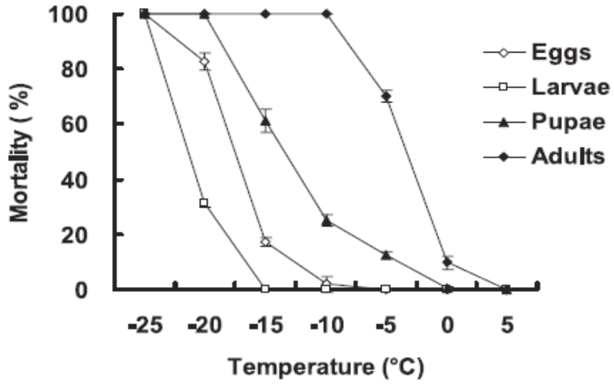


Table 1. Lt50 (d) limits of 4-5th instar larvae exposed to low temperatures

Temp	Lt50 (d)	Lt50 (w)
-25	0	0.0
-20	0.1	0.0
-15	14.7	2.1
-10	35.8	5.1
-5	55.7	8.0
0	72.6	10.4
5	65.4	9.3
25	69	9.9

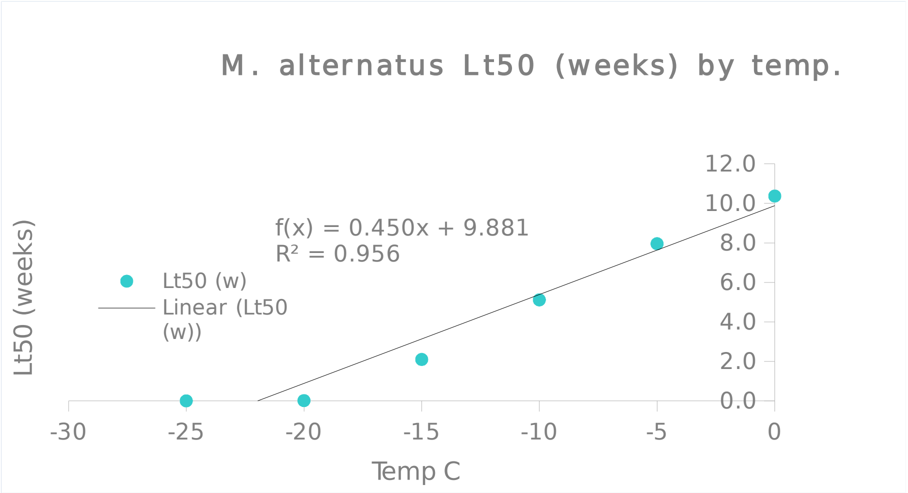
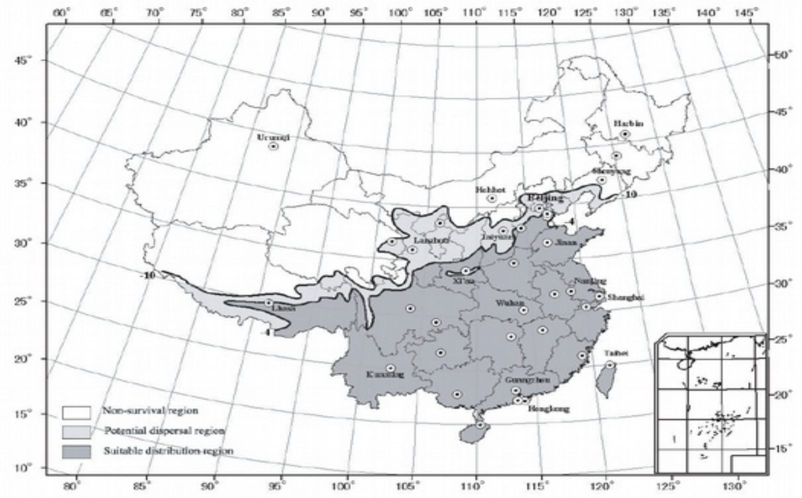


Figure 7. Potential distribution based on '-10 and -4C isotherms of avg. Jan mean temps (1961-1990)

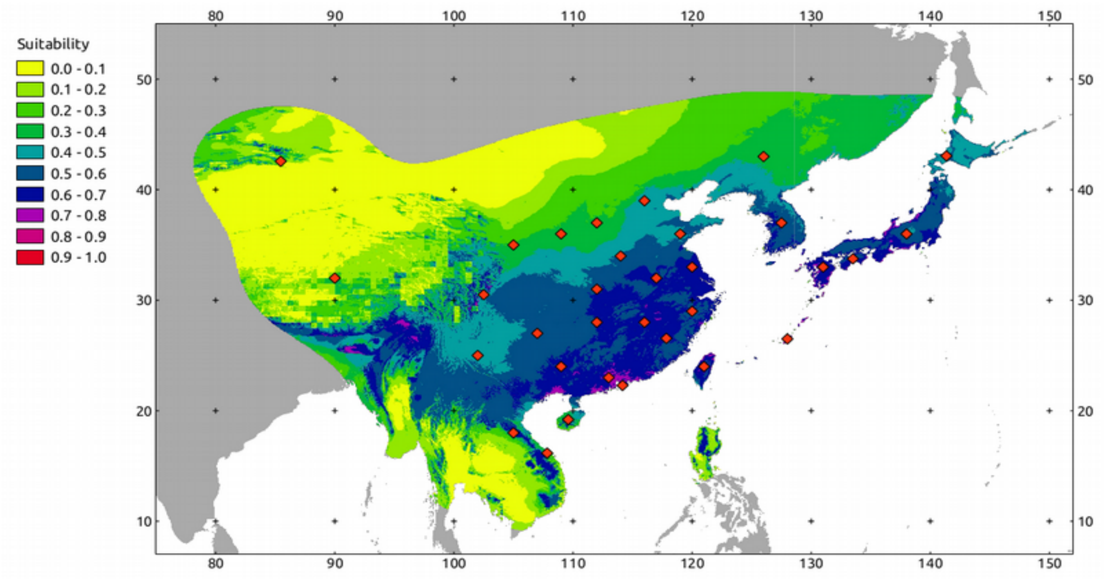


9. Estay, S., F. Labra, R. Sepulveda, and L.D. Bacigalupe. 2014. Evaluating habitat suitability of *Monochamus* spp through climate-based niche modeling. PLoS ONE 9:e102592.

- Estimated climate suitability for five North American and four Eurasian *Monochamus* species using the Maxent approach
- For all species, total annual precipitation was the most important variable for the species in North America and in Eurasia
- 95% geographic kernel showed that *M. alternatus* occurred in

Variable	Value	Definition
T Ann	-11.5-28C	Mean annual temperature
T Col	-25.5-26.5	Mean temp of coldest month
T War	-4-30.5	Mean temp of warmest month
ADD	0-8448	Annual accumulated degree-days
% RH	0-83.3	Annual mean relative humidity
PP	0-5576	Total annual precipitation
Altitude	-2-6512	Altitude

- The projected distribution in Asia is similar to the CLIMEX model (Source 10) below, except several points fall outside the suitability envelope (EI > 0)



Projection of the fitted model onto the 95% geographical kernel for M. alternatus (Fig. S6)

10. Kim, J., H. Jung, and Y-H Park. 2016. Predicting potential distribution of *Monochamus alternatus* Hope responding to climate change in Korea. Korean Journal of Applied Entomology. 55:501-511.

- Predicted the spatial distribution of the beetle in Korea under current and future climcates using CLIMEX
- They used climate data were a 10-yr average of data from 68 meterological stations (2006-2015)
- Their parameter sets included different values for development params DV0, DV1, DV2, DV3, and TTCS (cold stress threshold)

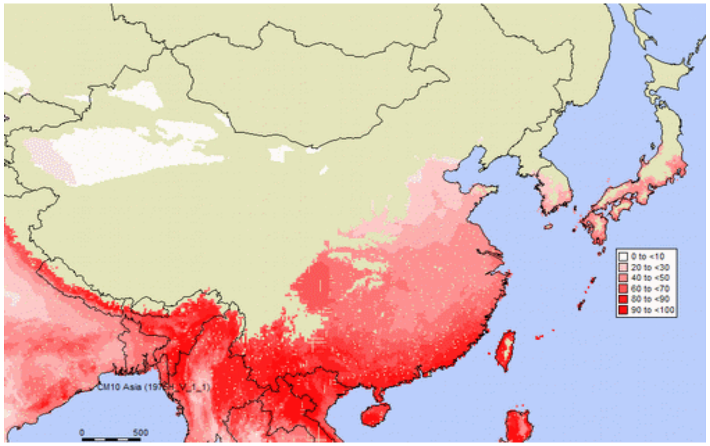
- An error matrix method was used to select and simulate the parameter sets showing the highest correlation with the actual distribution
- Results for future climate conditions showed a gradual expansion of the species throughout Korea
- It appears that cold stress contributes to low EI values at about 70 cold stress units (see white paper)
- It appears that their analysis supported Parameter Set 0 as the best set, although the paper being written in Korean makes this sort of unclear

Table 1**.** Initial parameter values of CLIMEX model

*** Note:** it is unclear if all of these values were used in their final model. The paper is written in Korean.
The word "initial" makes this unclear.

CLIMEX parameter	Code	Value	Notes
Temperature			
Lower temperature threshold (°C)	DV0	10.8	Set 0
Lower optimal temperature (°C)	DV1	15	Set 0
Upper optimal temperature (°C)	DV2	30	Set 0
Upper temperature threshold (°C)	DV3	33	Set 0
Degree-days per generation (°C days)	PDD	1690	
Moisture			
Lower soil moisture threshold	SM0	0.1	
Lower optimal soil moisture	SM1	0.55	
Upper optimal soil moisture	SM2	1.35	
Upper soil moisture threshold	SM3	4	
Cold stress			
Cold stress temperature threshold (°C)	TTCS	0	
Cold stress temperature rate (week–1)	THCS	–0.0008	
Heat stress			
Heat stress temperature threshold (°C)	TTHS	33	
Heat stress temperature rate (week–1)	THHS	0.0001	
Dry stress			
Dry stress threshold	SMDS	0.25	
Dry stress rate (week–1)	HDS	–0.001	
Wet stress			
Wet stress threshold	SMWS	4	
Wet stress rate (week–1)	HWS	0.0001	

Map of Ecoclimatic Index



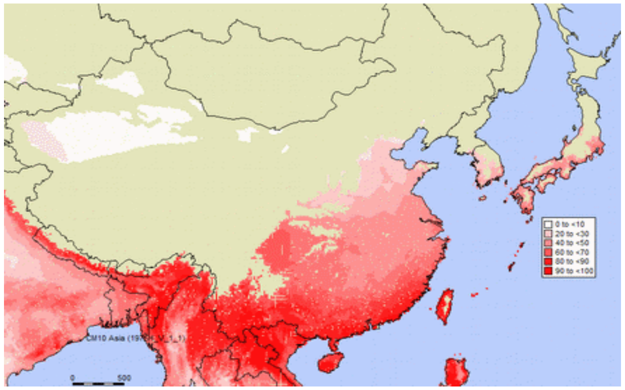
11. Modifications to CLIMEX model of Kim et al. (2016) [Source 10]

- There are two issues with Kim et al's (2016) CLIMEX model:
    1) several localities from Estay et al. map (Estay et al. 2014; source 9) fall within unsuitable areas according to CLIMEX (see below)
    2) the species does not exhibit increased mortality until temperatures drop below 0C (Ma et al. 2006; source 8), but their TTCS is 8C
- Insufficient degree-days accumulate at northern range limit; the species is not excluded from cold stress even when TTCS is set very low (e.g., TTCS = -5)
- Most likely the species persists in these areas by taking more than 1 year to complete it's life cycle...
- Nevertheless the TTCS value was lowered from 8 to 0C, because Ma et al.'s (2006)[source 8] experiments support this value
- Outputs for EI were very similar, but now cold stress is lower in areas where the excluded localities are situated, so this is prbably more realistic

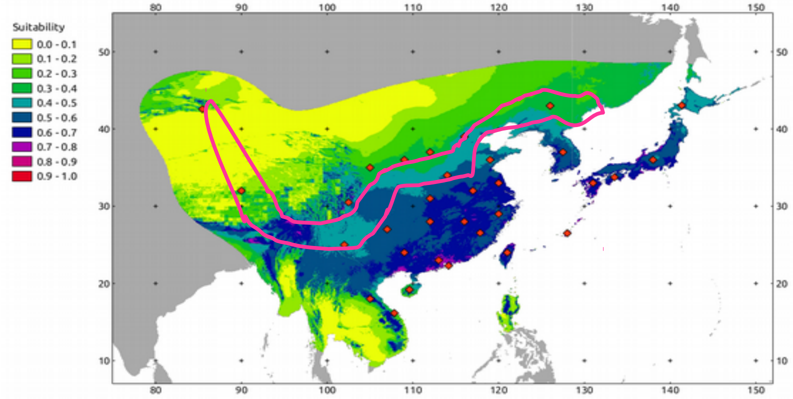
Kim et al. 2016 CLIMEX model vs. Estay et al. 2014 Maxent model

Several northern localities where the species is established (outlined in pink, below) are excluded in the CLIMEX model (EI = 0)
Cold stress may be too high in the CLIMEX model, resulting in the exclusion of these localities

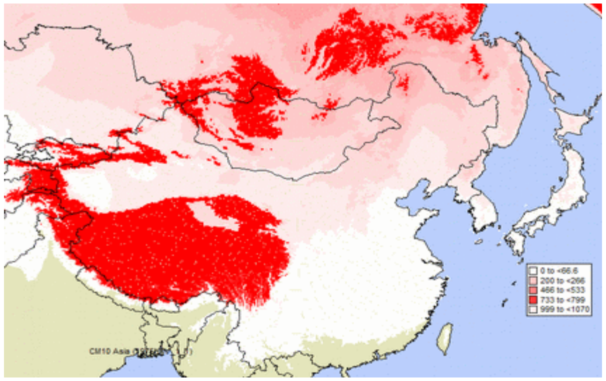
CLIMEX model (Ecoclimatic index)



Maxent model



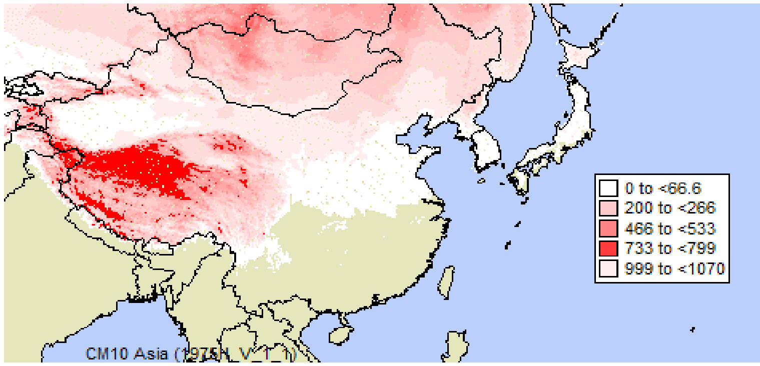
CLIMEX model (Cold stress)



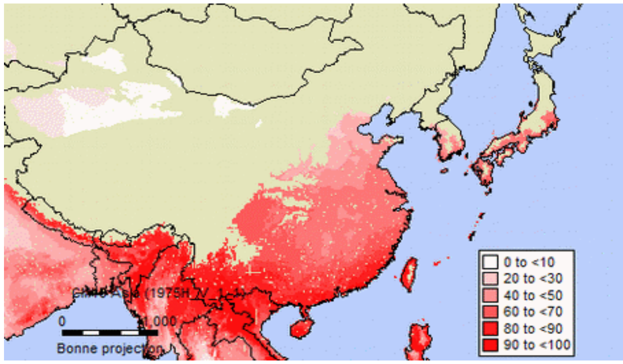
Revised CLIMEX model (TTCS = 0 and THCS = -0.0003) - below

The cold stress threshold was decreased in the modified CLIMEX model, but EI values did not change much

Cold Stress



Ecoclimatic Index

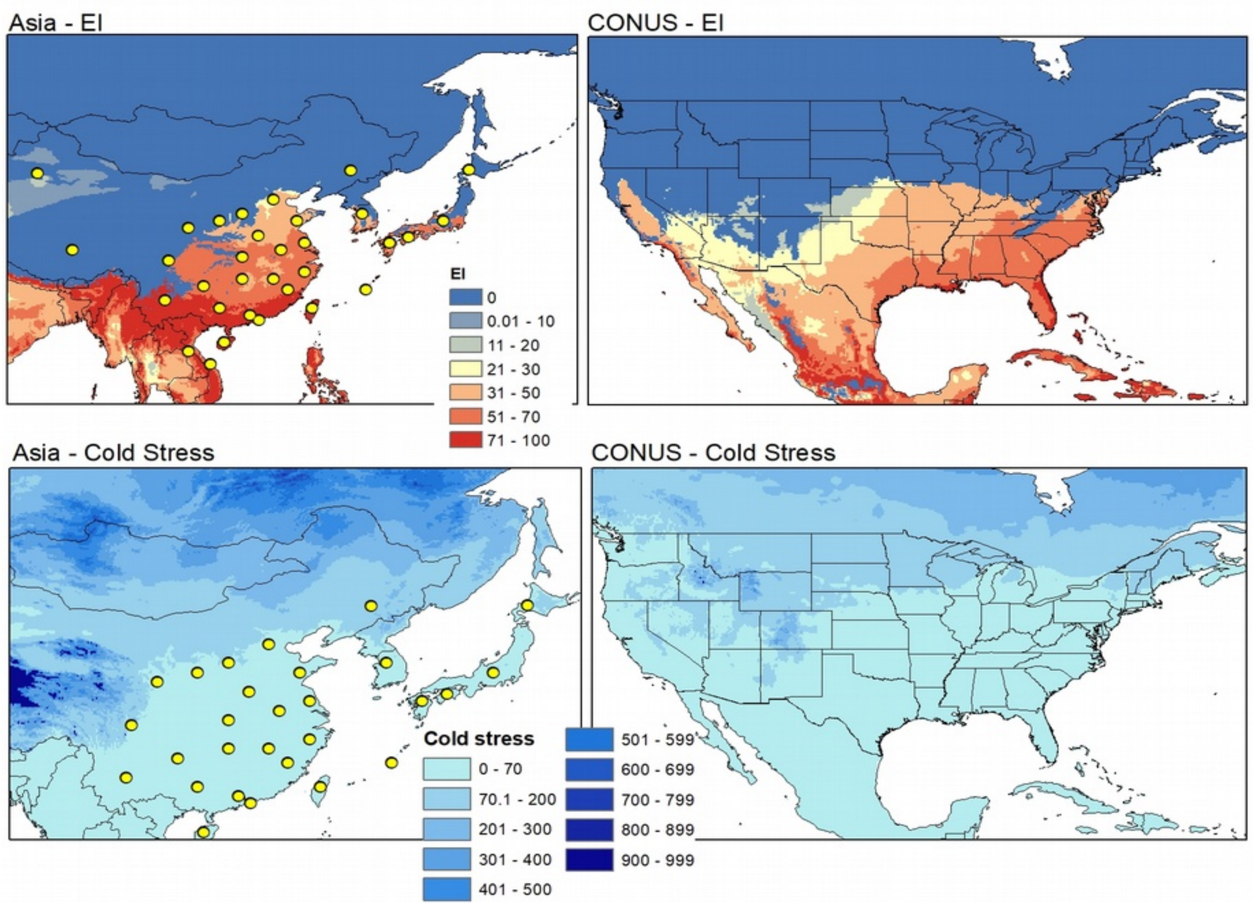


Comparison of EI and cold stress values in Asia and CONUS in using CLIMEX model w/ TTCS = 0 and THCS = -0.0003

Yellow dots are the localities for *M. alternatus* presented in Estay et al. (2014)

Note that the cold stress = 70 break line corresponds roughly with the northernmost (-10C) isotherm of Ma et al. 2006 (Source 8)

This suggests that the species would not be prevented from establishing in areas where cold stress is < 70



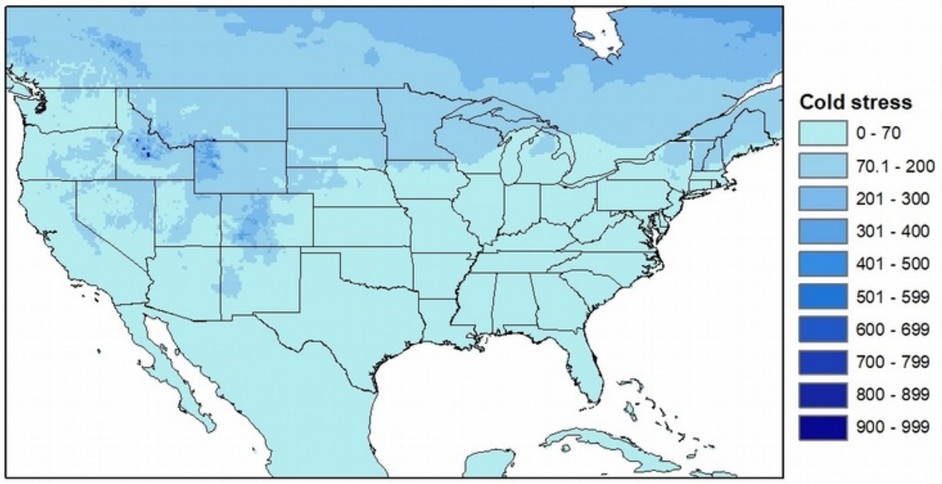
12. DDRP climate suitability model calibrated using modified CLIMEX model (source 11)

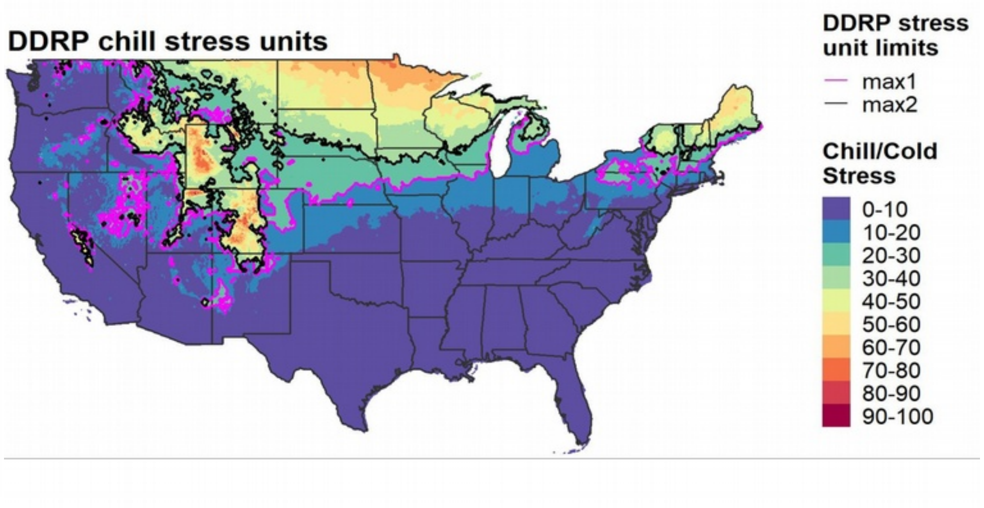
Fine-tuning stress parameters and limits in accordance w/ CLIMEX model resulted in:

	Value	Units
chill stress threshold	-4	C
limit 1 (mod. chill stress)	525	DDC
limit 2 (sev. chill stress)	800	DDC

All but a single locality record in the native range occur in areas where cold stress is less than
70 in CLIMEX, so the max2 limit in DDRP was adjusted to generally match the boundary where CLIMEX cold stress rose above 70

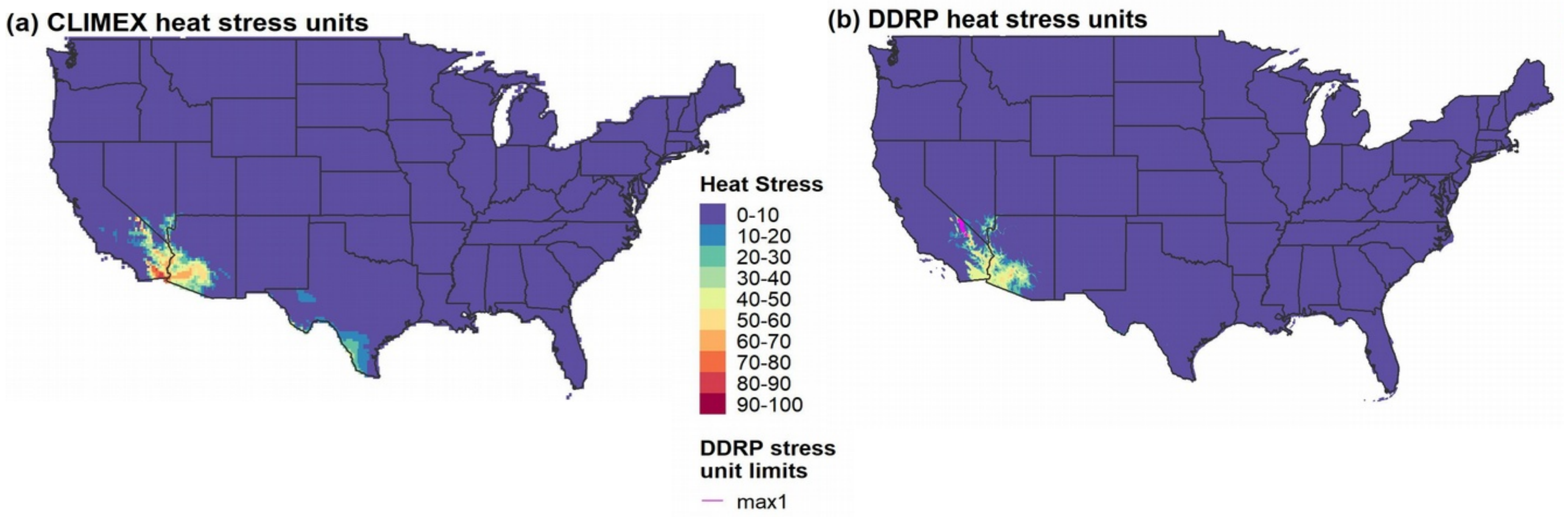
(a) CLIMEX cold stress units





	Value	Units
heat stress threshold	36	C
limit 1 (mod. heat stress)	800	DDC
limit 2 (sev. heat stress)	1100	DDC

EI values were not lowered by heat stress in CLIMEX, so set heat stress limits very high in DDRP



Thresholds, degree-days, events and climate suitability params used in Japanese Pine Sawyer Beetle model:

Parameter abbr.	Description	degF	degC	DDF	DDC
eggLDT	egg lower dev threshold	54.0	12.2	-	-
eggUDT	egg upper dev threshold	95.0	35.0	-	-
larvaeLDT	larvae lower dev threshold	54.0	12.2	-	-
larvaeUDT	larvae upper dev threshold	95.0	35.0	-	-
pupaeLDT	pupae lower dev threshold	54.0	12.2	-	-
pupaeUDT	pupae upper dev threshold	95.0	35.0	-	-
adultLDT	adult lower develpmental threshold	54.0	12.2	-	-
adultUDT	adult upper dev threshold	95.0	35.0	-	-
eggDD	duration of egg stage in DDs	-	-	149	83
larvaeDD	duration of larva stage in DDs	-	-	1164	647
pupaeDD	duration of pupa stage in DDs	-	-	298	166
adultDD	duration of adult (preOV + 35% OV) stage in DDs	-	-	373	207
OWpupaeDD	DDs until pre-OV adults emerge (no OW pupae)	-	-		
eggEventDD	DDs into egg stage when hatching begins	-	-		
larvaeEventDD	DDs into larvae stage when mid-larval development occur	-	-		
pupaeEventDD	DDs into preOV stage when adults becoume active	-	-		
adultEventDD	DDs into adult stage when peak (30% OV) oviposition occ	-	-		
chillstress_threshold	chill stress threshold	24.8	-4.0	-	-
chillstress_units_max1	chill degree day limit when most individuals die	-	-	945	525
chillstress_units_max2	chill degree day limit when all individuals die	-	-	1440	800
heatstress_threshold	heat stress threshold	96.8	36.0	-	-
heatstress_units_max1	heat stress degree day limit when most individuals die	-	-	1440	800
heatstress_units_max2	heat stress degree day limit when all individuals die	-	-	1980	1100
distro_mean	average DDs to OW pupation	-	-	367	204
distro_var	variation in DDs to OW pupation	-	-	5400	3000
xdist1	minimum DDs (°C) to OW pupation	-	-	18	10
xdist2	maximum DDs (°C) to OW pupation	-	-	738	410
distro_shape	shape of the distribution	-	-		normal