Phenology/Degree-Day Model Analysis – July 24, 2020

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Asiatic rice borer *Chilo suppressalis* Walker (Lepidoptera: Crambiidae)

Hosts: rice, grasses, sorghum, corn Native to: Asia (temperate climates) Invaded areas include: N. Australia, W. Europe, Mexico, New Guinea

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

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International Rice Research Institute

Thresholds, degree-days, events and climate suitability params used in Asiastic Rice Borer model:

Parameter abbr.	Description	degF	degC	DDF	DDC
eggLDT	egg lower dev threshold	50.0	10.00	-	-
eggUDT	egg upper dev threshold	100.4	38.0	-	-
larvaeLDT	larvae lower dev threshold	50.0	10.00	-	-
larvaeUDT	larvae upper dev threshold	100.4	38.0	-	-
pupaeLDT	pupae lower dev threshold	50.0	10.00	-	-
pupaeUDT	pupae upper dev threshold	100.4	38.0	-	-
adultLDT	adult lower develpmental threshold	50.0	10.00	-	-
adultUDT	adult upper dev threshold	100.4	38.0	-	-
eggDD	duration of egg stage in DDs	-	-	185	103
larvaeDD	duration of larva stage in DDs	-	-	935	520
pupDD	duration of pupa stage in DDs	-	-	225	125
adultDD	duration of pre-OV plus time to 50% OV in DDs	-	-	143	79
OWlarvaeDD	DDs until OW larvae first pupation	-	-	423	235
eggEventDD	DDs into egg stage when hatching begins	-	-	167	93
larvaeEventDD	DDs until mid-larval deveopment	-	-	469	261
pupaeEventDD	DDs until adult emergence	-	-	216	120
adultEventDD	DDs until first egg laying	-	-	44	25

coldstress_threshold	cold stress threshold	-4.0	-20	-	-
coldstress_units_max1	cold stress degree day limit when most individuals die	-	-	720	400
coldstress_units_max2	cold stress degree day limit when all individuals die	-	-	1440	800
heatstress_threshold	heat stress threshold	102.2	39.0	-	-
heatstress_units_max1	heat stress degree day limit when most individuals die	-	-	450	250
heatstress_units_max2	heat stress degree day limit when all individuals die	-	-	1350	750

distro_mean	average DDs to OW larvae first pupation	423	235
distro_var	variation in DDs to OW larvae first pupation	9000	5000
xdist1	minimum DDs (°C) to OW larvae first pupation	135	75
xidst2	maximum DDs (°C) to OW larvae first pupation	990	550
distro_shape	shape of the distribution		normal

Degree-day / phenology requirements

Points added to force x-intercept or dropped as outliers from linear response highlighted in yellow

Methods: Force regression to a common x-intercept of 10.0C for all life stages (standard practice for these analyses).

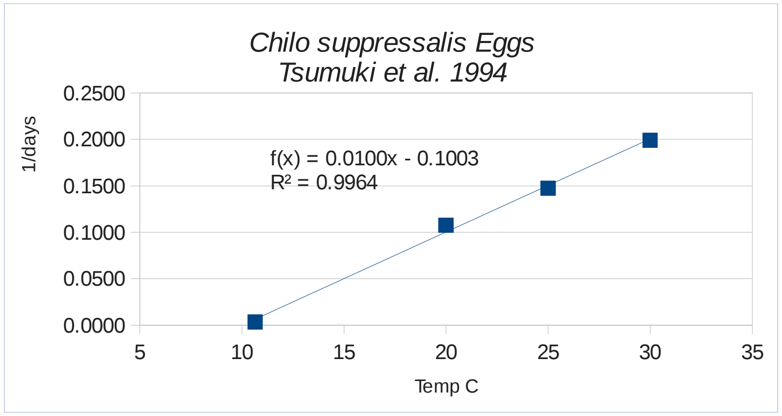
1. Tsumuki, H, T. Take, K. Kanehisa, T. Saito, and Y.I. Chu. 1994. Effect of temperature on the development and voltinism of the rice stem borer, *Chilo suppressalis* (Lepidoptera: Pyralidae) in Taiwan. Eur. J. Entomol. 91: 477-479.

Notes:

- Larval diapause in Japan, mostly bivoltine but trivoltine in far S. Japan, univoltine in far N. Japan.
- This species is daylength sensitive for winter diapause inducement in cooler parts of its range.
- In Taiwan (25N lat) and southern parts of its range, passes the winter without diapause
- Tlow in Taiwan somewhat lower than further North as in Japan
- Solved for Tlows of 8.9, 9.2, 10.5 for eggs, larvae, and female pupae
- This species well known for biotypes with different life histories: therefore should probably weight the more temperate (Japanese) populations more heavily than this more sub-tropical population in Taiwan.

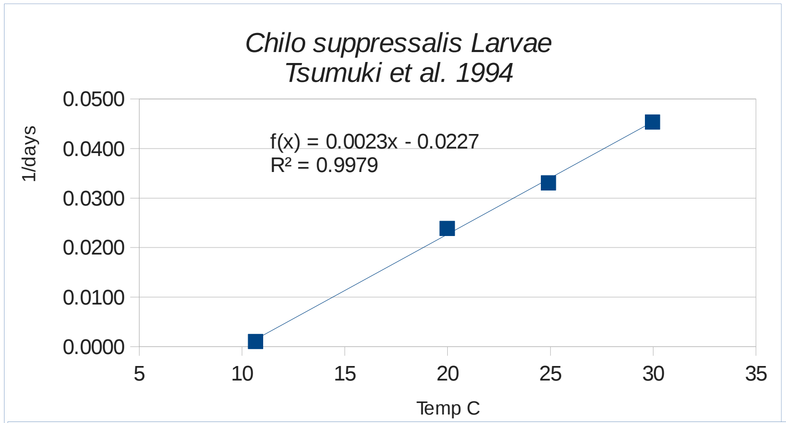
Methods: Use temperature development data and the x-intercept method to determine Tlow and DD requirements for all stages studied. Use Webplotanalyzer to estimate data from Fig. 1.

Eggs	TempC	1/days	days
	10.655	0.0035	283
	20	0.1076	9.3
	25	0.1474	6.8
	30	0.1992	5.0
	intercept	-0.1003	
	slope	0.0100	
	R-sq	0.9964	
	X-intercept	10.0006	
	DDs	99.7	



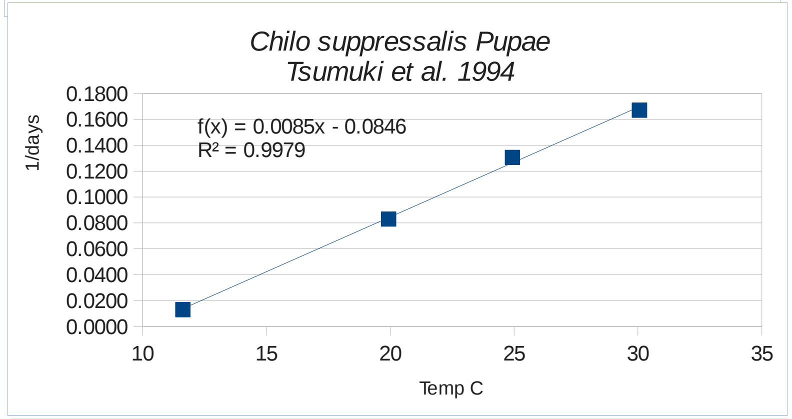
Larvae

TempC	1/days	days
10.65	0.0011	939.6
20	0.0239	41.9
25	0.0331	30.2
30	0.0454	22.0
intercept	-0.0227	
slope	0.0023	
R-sq	0.9979	
X-intercept	10.0002	
DDs	440.4	



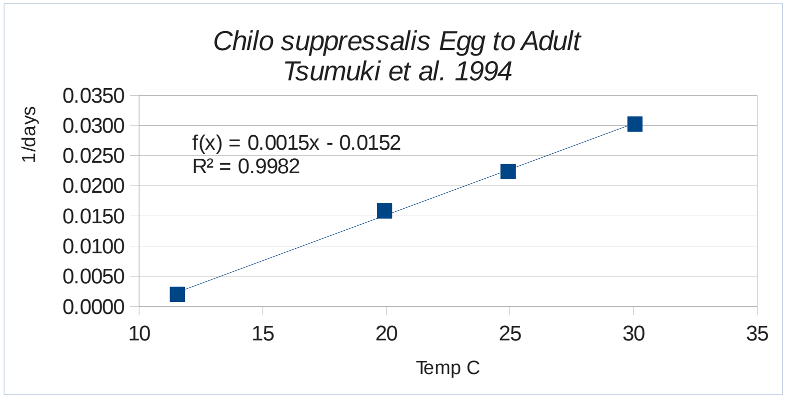
Pupae (female)

TempC	1/days	days
11.623	0.0131	76.465
20	0.0831	12.0
25	0.1307	7.7
30	0.1671	6.0
intercept	-0.0846	
slope	0.0085	
R-sq	0.9979	
X-intercept	10.0000	
DDs	118.1	



Egg to adult (female pupae)

TempC	1/days	days
11.546	0.0020	500
20	0.0158	63.3
25	0.0224	44.7
30	0.0303	33.1
intercept	-0.0152	
slope	0.0015	
R-sq	0.9982	
X-intercept	10.0006	
DDs	659.6	



Results: Using a Tlow of 9.45C, the DD req.s for egg, larvae, pupae, and egg to adult were: 103, 455, 122, and 680 DDC. R-sq values were high at 0.998 or higher for all stages. Upon analysis of sources below, re-solved for Tlow of 10C, resulting in DD req.s of 100, 440, 118, and 660 (same stages), with R-sq values of 0.996 or higher.

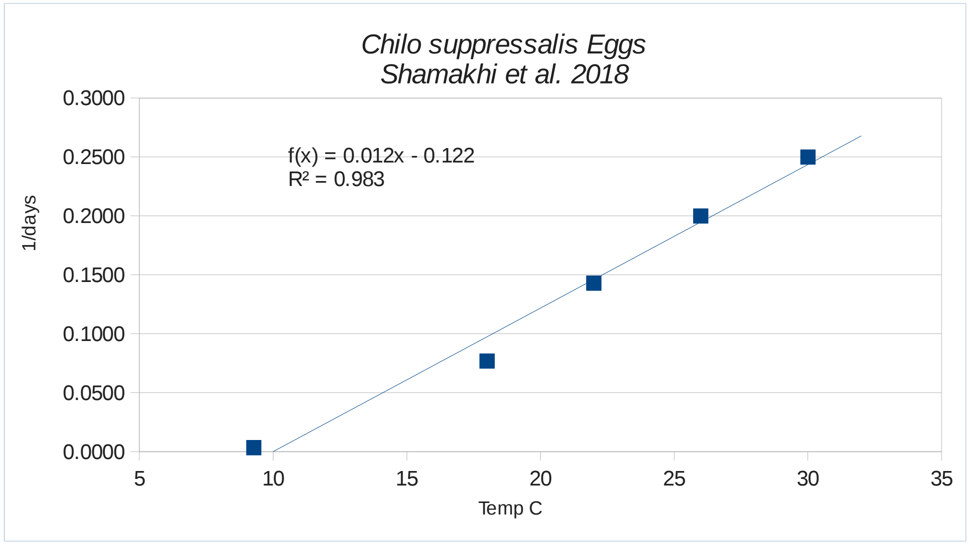
2. Shamakhi, L, A. Zibaee, A. Karimi-Malati, and H. Hoda. 2018. A laboratory study on the modeling of temperature-dependent development and antioxidant system of *Chilo suppressalis* (Lepidoptera: Cambidae). J. Insect Science 18:1-11.

- Population from Amol Iran **(**near S. shore Caspian sea NE of Tehran; 37N Lat.**)**
- 70% RH, 16:8 L:D
- using x-intercept linear model, solved for 10C Tlow
- found that development slowed at 34C so dropped as non-linear

Eggs

TempC	1/days	days
9.2778	0.0033	300
18	0.0769	13.0
22	0.1429	7.0
24		5.0
26	0.2000	5.0
30	0.2500	4.0
32		4.0
34		4.0

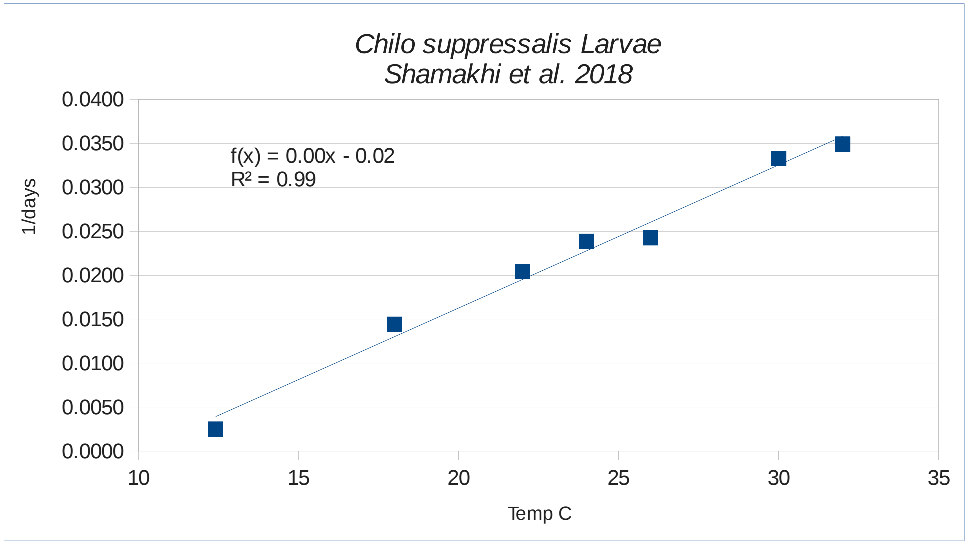
intercept	-0.1218
slope	0.0122
R-sq	0.9831
X-intercept	10.0002
DDs	82.1



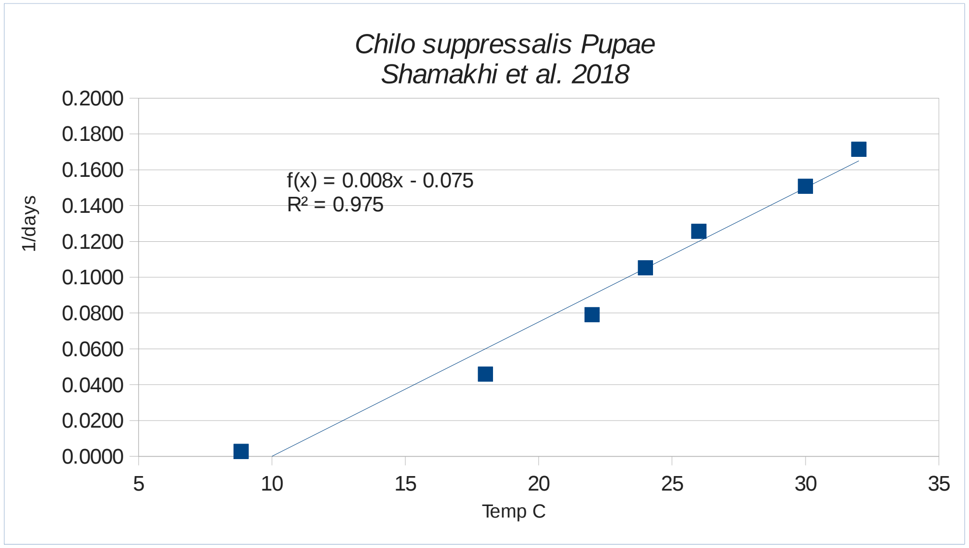
Larvae

TempC	1/days	days
12.412	0.0025	400
18	0.0144	69.3
22	0.0204	49.0
24	0.0238	41.9
26	0.0242	41.3
30	0.0333	30.1
32	0.0349	28.7
34		31.5

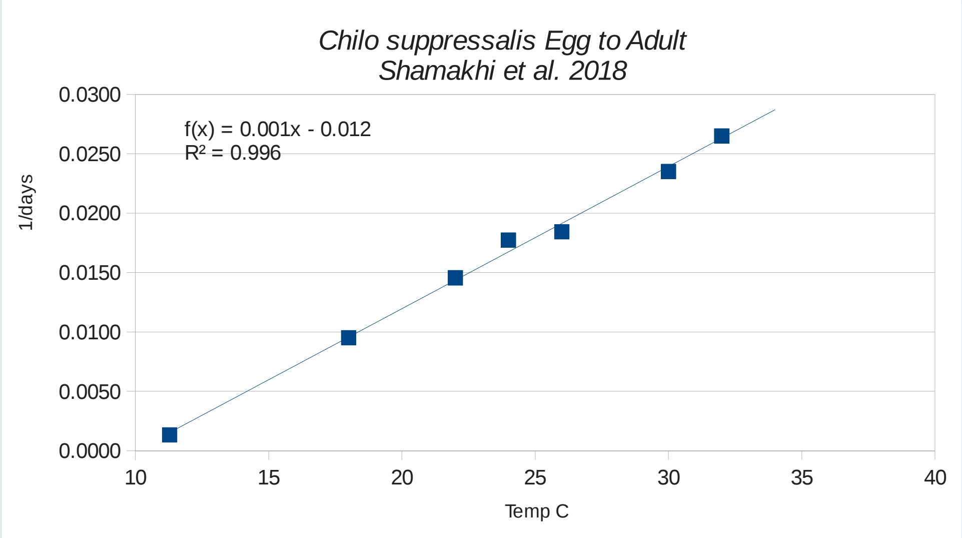
intercept	-0.0163
slope	0.0016
R-sq	0.9859
X-intercept	10.0005
DDs	614.8



Pupae	TempC	1/days	days
	8.85	0.0029	350
	18	0.0460	21.7
	22	0.0791	12.6
	24	0.1053	9.5
	26	0.1256	8.0
	30	0.1508	6.6
	32	0.1715	5.8
	34		6.6
	intercept	-0.0750	
	slope	0.0075	
	R-sq	0.9753	
	X-intercept	10.0036	
	DDs	133.3	



Egg to adult	TempC	1/days	days
	11.281	0.0013	750
	18	0.0095	105.1
	22	0.0146	68.7
	24	0.0177	56.4
	26	0.0184	54.3
	30	0.0235	42.5
	32	0.0265	37.8
	34		39.5
	intercept	-0.0120	
	slope	0.0012	
	R-sq	0.9959	
	X-intercept	10.0000	
	DDs	836.0	



Results: Development rate was lower at 34C so this point was dropped. Using a forced Tlow of 10.0C (50F), DD requirements were 82, 615, 133, and 836 for eggs, larvae, pupae and egg to adults. R-sq values indicate excellent fit for all stages with 0.983, 0.986, 0.975, and 0.996 for eggs, larvae, pupae, and egg-to-adult stages.

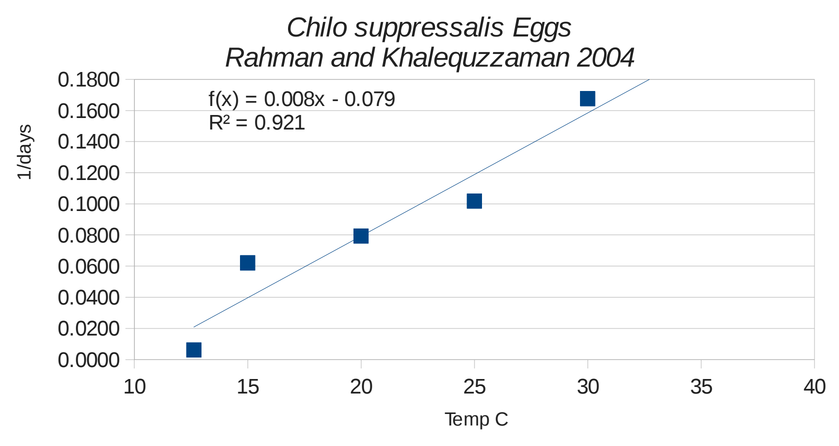
3. Rahman, M. T., and M. Khalequzzaman. 2004. Temperature requirements for the development and survival of rice stemborers in laboratory conditions. Entomol. Sin. 11: 47–60.

- Studies conducted in Bangladesh (25N Lat.) using 6 spp. including C. suppressalis at 7 temperatures, 70% RH, 12:12 L:D, rice variety BR14 used as food source.
- Used linear modeling to solve tor Tlow of 7.6, 8.8, and 6.8 C for egg, larval, and pupal stages.
- Estimate 7 generations/year in Rajshahi Bangladesh, similar to 2 related rice stemborers (C. polychrysa and C. partellus)

Eggs

TempC	1/days	days
12.6183	0.0063	160
15	0.0621	16.1
20	0.0792	12.6
25	0.1017	9.8
30	0.1675	6.0
35		7.4

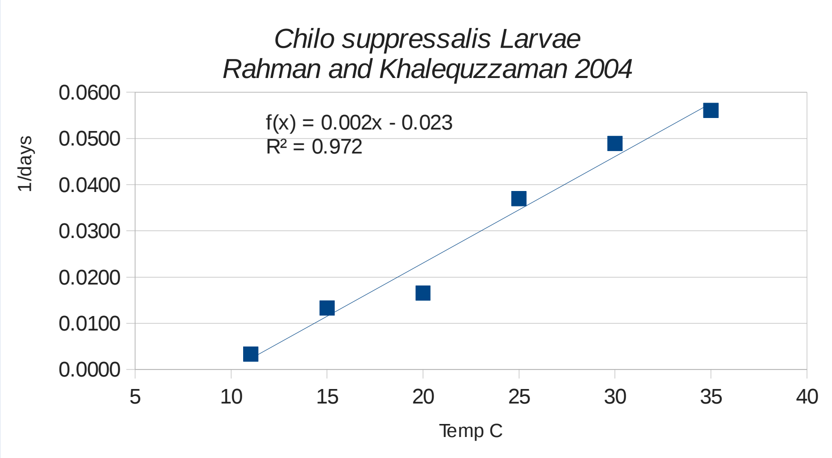
intercept	-0.0792
slope	0.0079
R-sq	0.9213
X-intercept	10.0000
DDs	126.2


Chilo suppressalis Eggs
Rahman and Khalequzzaman 2004

Larvae

TempC	1/days	days
11.0295	0.0033	300
15	0.0133	75.1
20	0.0166	60.4
25	0.0370	27.1
30	0.0489	20.5
35	0.0561	17.8

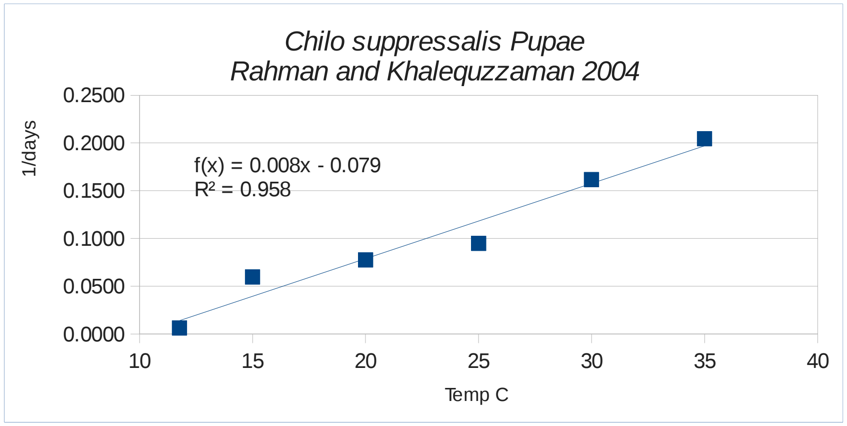
intercept	-0.0230
slope	0.0023
R-sq	0.9724
X-intercept	10.0000
DDs	434.1


Chilo suppressalis Larvae
Rahman and Khalequzzaman 2004

Pupae

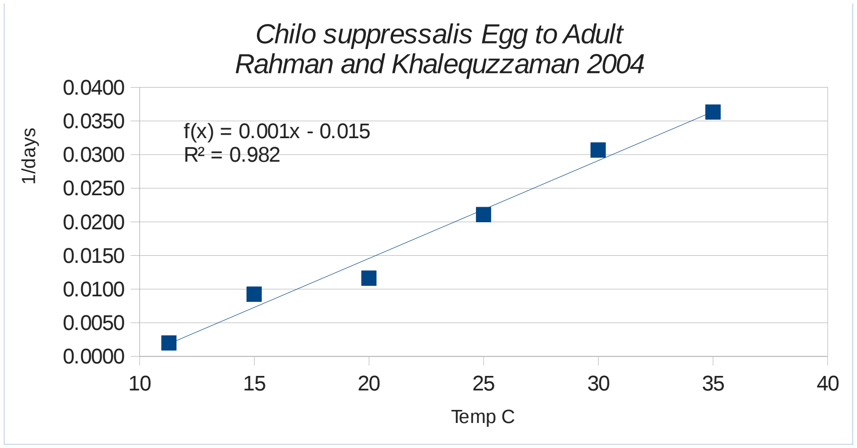
TempC	1/days	days
11.763	0.0063	160
15	0.0597	16.8
20	0.0777	12.9
25	0.0950	10.5
30	0.1618	6.2
35	0.2045	4.9

intercept	-0.0788
slope	0.0079
R-sq	0.9578
X-intercept	10.0002
DDs	126.9


Chilo suppressalis Pupae
Rahman and Khalequzzaman 2004

Egg to adult	TempC	1/days	days
	11.272	0.0020	500
	15	0.0093	108.0
	20	0.0116	85.9
	25	0.0211	47.4
	30	0.0307	32.6
	35	0.0363	27.5

intercept	-0.0146
slope	0.0015
R-sq	0.9824
X-intercept	10.0000
DDs	687.1



Female adults – time to mean period of reproduction (estimate)

Values provided in text and Table 4: single temp of 26.98C; duration in days = 4.97

Estimate using Tlow = 10.0 C

(26.98 – 10.0) x 4.97 d 79.42 (Tlow=10.0C) Modified Tlow

Generation time in DD Tlow = 10

Egg + Larvae + Pupae + mean reproduction time

766 DD at Tlow = 10.0 C

Results: Using a Tlow of 10.0C, development required 126, 434, 126, 687, and 79 DD for eggs, larvae, pupae, egg-to-adult, and mean time to 50% oviposition, respectively. Whole generation time was the sum of these values, 766 DD. While eggs slowed development at 35C (and the point was drpped), larvae and pupae responded linearly so these points were retained. R-sq values suggest very good fit with 0.921, 0.972, 0.958, and 0.982 for eggs, larvae, pupae, and egg-to-adult stages.

4. Quan, W, W. Liu, R. Zhou, S. R. Qureshi, N. Ding, W. Ma, C. Lei and X. Wang. 2016. Do differences in life-history traits and the timing of peak mating activity between Host-associated populations of *Chilo suppressalis* have a genetic basis? Ecol. Evol. 6:4478-4487.

- Wuhan China **(**30N Lat.**)**
- Compared rice and water-oat host races for larval development and time to mating
- reared at 28 deg. C, 80% RH, LD 15:9
- 60% mated within 24 hr after eclosion
- data show mating within hours of onset of darkness, assume 24 hrs after eclosion

host	Days larval devel	Estim. DDs (Tlow=10C)
water oats	29	522
rice	36.5	657
average		589.5
	Adults – days to mating (approx. estim.)	
	1.2	22

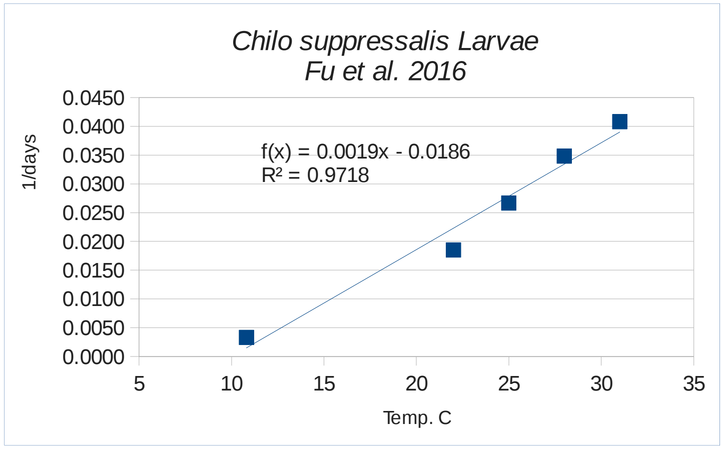
Results: Larvae develop faster reared on water oats than on rice, averaging 590 DD (water oats) and 657 DD (rice). Avg 1.2 days or 22 DD between emergence and mating.

5. Fu, D.M, H.M He, C. Zou, H.J. Xiao, F.S. Xue. 2016. Life-history responses of the rice stem borer *Chilo suppressalis* to temperature change: breaking the temperature-size rule. J. Thermal Biology. 61:115-118.

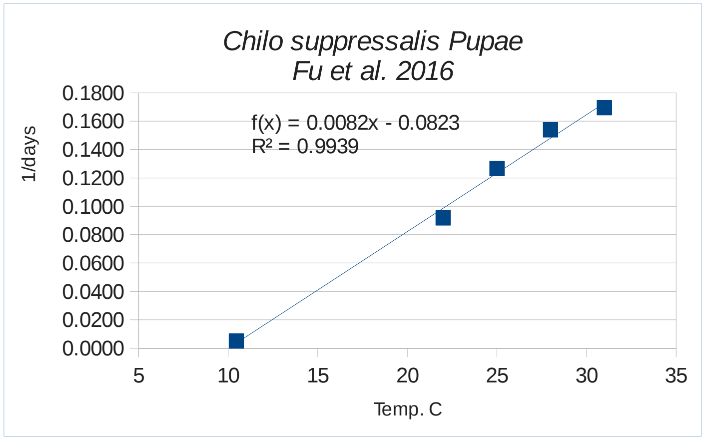
- population from Wuchang city, Heilongjiang Province, China. (44.55 Deg. N.)
- nearly all univoltine before diapause; a few produce a second generation

From Fig. 1 – Larval and pupal development times (using females).

Larvae	Temp C	1/days	Days
	10.801	0.0033	300
	22	0.0185	54
	25	0.0267	37.5
	28	0.0348	28.7
	31	0.0408	24.5
	intercept	-0.0186	
	slope	0.0019	
	R-sq	0.9718	
	X-intercept	10.0000	
	DDs	537.9	



Pupae	Temp C	1/days	Days
	10.452	0.0050	200
	22	0.0917	10.9
	25	0.1266	7.9
	28	0.1538	6.5
	31	0.1695	5.9
	intercept	-0.0823	
	slope	0.0082	
	R-sq	0.9939	
	X-intercept	10.0000	
	DDs	121.6	



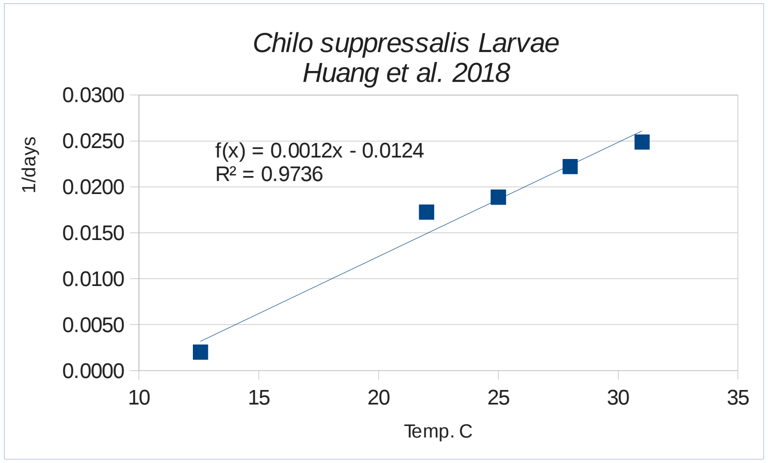
Results: Larval and pupal development times were 538 and 122 DD, respectively.

6. Huang, X.L., L. Xiao, H.M. He, F.S. Xue. 2018. Effect of rearing conditions on the correlation between larval development time and pupal weight of the rice stem borer, *Chilo suppressalis*. Ecol. Evol. 8:12694-12701.

- studies in Nanching, China (32N Lat.)

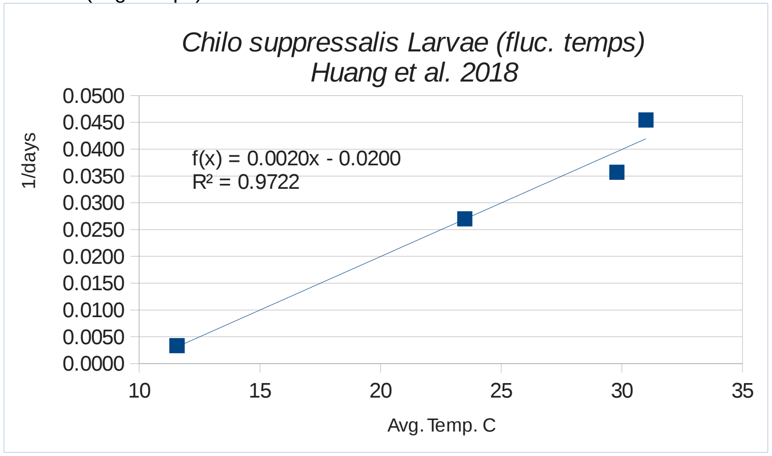
From Fig. 3 – Larval development times (using females).

Larvae	Temp C	1/days	Days
	12.565	0.0020	500
	22	0.0172	58
	25	0.0189	53
	28	0.0222	45
	31	0.0249	40.2
	intercept	-0.0124	
	slope	0.0012	
	R-sq	0.9736	
	X-intercept	10.0007	
	DDs	804.6	



From Fig. 4 – Larval development times (using females) under fluctuating field conditions (avg. temps)

Larvae	Temp C	1/days	Days
	11.567	0.0033	300
	23.5	0.0270	37
	29.8	0.0357	28
	31	0.0455	22
	31		
	intercept	-0.0200	
	slope	0.0020	
	R-sq	0.9722	
	X-intercept	10.0005	
	DDs	500.9	



Results: Constant temperature results not in accord with other studies in that larval development was exceedingly slow. Larval development under field conditions are in good accord with other studies.

7. Comparison / synthesis of above results

determined through subtraction, addition, or average of other studies represented in table

Source	Country	Approx. Latitude	Egg	Larvae	Pupae	Egg-to-adult	Time to mating	Pre-OV	Female longevity	Approx. mid OV	Full Gen. assume ca. mid OV
1. Tsumuki et al. 1994	Taiwan	25N	100	440	118	660					
2. Shamakhi et al. 2018	Iran	37N	82	615	133	836					
3. Rahman and K. 2004	Bangladesh	25N	126	434	127	687				79	766
4. Quan et al. 2016	China	30N	103	590	125	817	22				
5. Fu et al. 2016	China	45N	103	538	122	762					
6. Huang et al. 2018	China	32N		501							
Avg of observed			**103**	**520**	**125**	**728**	**22**			**79**	**807**

Results: While there is little info on adult activity, using the one study available (Rahman et al. 2004) where we estimated emergence to mid- or peak-OV at 79 DD, we otherwise have good agreement in finding average DD requirements for eggs, larvae, pupae, and egg-to-adults at 103, 520, 125, and 728 DD, respectively. Full generation time is estimated from these values at 807 DD using a 10C lower threshold.

Springtime Flight Estimation

8. Kishino, K. 1974. Local differences of seasonal life cycle in rice stem borer, *Chilo suppressalis* Walker. Japan Agric. Res. Quart. 8:72-77.

- Data from a wide range of latitudes in Japan comparing moth appearance, voltinism, diapause etc.
- Mostly bivoltine at latitudes from 32-36 Deg, uinvoltine 36 - 41 deg. N.

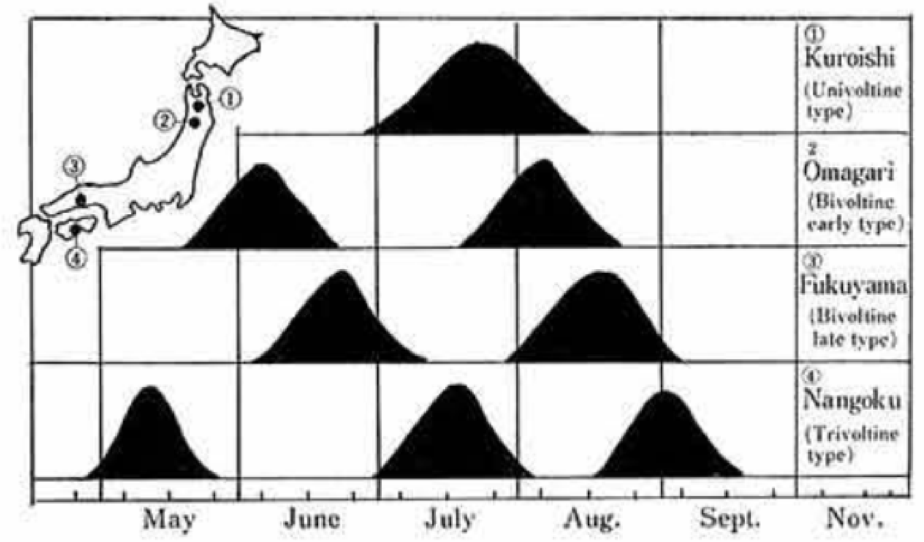


Fig. 4. Diagram of moth appearance in the different seasonal life cycle areas

From Fig. 4:

Methods: Estimate DDs for first and peak moths for the four locations depicted in Fig. 4 using available data (recent data from degreedays.net; two weather stations each).

Trivoltine location – Nangoku Japan **Degree-Days (calculated using degreedays.net)**

		Location 1 (RJOK)			Location 2 (47893)					
		2018	**2019**	**2020**	**2018**	**2019**	**2020**	**AVG**	**Gen Diffs**	**No. Gens/yr**
OW Gen.										
1st moths	04/28/00	321	275	283	338	288	295	300		
peak moths	05/13/00	447	396	422	463	410	437	429		
1st Gen										
1st moths	06/28/00	1015	954	992	1042	975	1026	1001	701	
peak moths	0716/00	1313	1211	1247	1347	1238	1290	1274	845	
2nd Gen										
1st moths	08/16/00	1885	1758	1806	1937	1802	1865	1842	842	
peak moths	09/02/00	2177	2032	2113	2236	2080	2183	2137	863	
End-of-seaso	10/20/00	2785	2741	2711	2855	2805	2796	2782		3.4

Bivoltine location – Fukuyama Japan **Degree-Days (calculated using degreedays.net)**

		Location 1 (RJOA)			Location 2 (47767)					
		2018	**2019**	**2020**	**2018**	**2019**	**2020**	**AVG**	**Gen Diffs**	**No. Gens/yr**
OW Gen.										
1st moths	06/03/00	456	413	382	520	500	499	462		
peak moths	06/22/00	648	614	609	745	732	754	684		
1st Gen										
1st moths	07/30/00	1252	1120	1118	1413	1316	1332	1259	797	
peak moths	08/20/00	1610	1478	1460	1814	1719	1721	1634	950	
End-of-seaso	10/20/00	2289	2200	2106	2608	2568	2453	2371		2.9

Bivoltine location – Omagari Japan **Degree-Days (calculated using degreedays.net)**

		Location 1 (RJSC)			Location 2 (RJSY)					
		2018	**2019**	**2020**	**2018**	**2019**	**2020**	**AVG**	**Gen Diffs**	**No. Gens/yr**
OW Gen.										
1st moths	05/17/00	200	179	178	158	136	138	165		
peak moths	06/07/00	403	406	374	317	340	293	356		
1st Gen										
1st moths	07/18/00	946	860	879	804	781	772	840	676	
peak moths	08/06/00	1287	1193	1193	1130	1099	1058	1160	805	
End-of-seaso	10/20/00	2099	2087	1945	1957	2019	1848	1993		2.5

Univoltine location – Kuroishi Japan **Degree-Days (calculated using degreedays.net)**

		Location 1 (RJSA)			Location 2 (47575)					
		2018	**2019**	**2020**	**2018**	**2019**	**2020**	**AVG**	**Gen Diffs**	**No. Gens/yr**
OW Gen.										
1st moths	06/28/00	338	384	318	424	450	402	386		
peak moths	07/23/00	622	604	646	724	705	749	675		
End-of-seaso	10/20/00	1402	1504	1346	1648	1753	1569	1537		1.9

Results:

1) First moths were earliest for uivoltine location Omagari at ca. 165 DDC, then for trivoltine location Nangoku at 300 DDC, followed by univoltine location Kuroishi At 386 DD and by bivoltine location Fukuyama at ca. 462 DD. This suggests that photoperiod should be added to the modeling platform to accommodate different emergence times depending on latitude and locally adapted critical photoperiods for spring initiation of development. In the meantime, the more conservative estimates of 165 DD first and 356 DD peak OW generation flight can be used for the conterminous US.
2) Generation time differences between first and peak moths were well within expected average of 807 DD/gen., which helps support this data set as valid and that this older report does not differ markedly from the 2018-2020 climate data used for this analysis.
3) Season-long DDs generally matched well in comparison to estimated generation time of 807 DD. With univotine = 1.9 gen/yr, bivoltine = 2.5-2.9 gen/yr, and trivoltine = 3.4 gen/yr, the species appears well-adapted to recent average heat units per YEAR (although we could predict that after 45+ years the univoltine location has at least a partial second generation, for example).

- From Fig. 5 - Critical photoperiod for diapause highly dependent on latitude of population:

Location	Latitude	CP50 (Critical photoperiod for 50th percentile), hr	
Nangoku	33.6 N	14.1	Trivoltine
Fukuyama	34.4 N	14.6	Bivoltine
Omagari	39.5 N	15.35	Bivoltine
Kuroishi	40.6 N	15.45	Univoltine

Results:

These estimated critical photoperiod vs. latitude results mainly apply to a future version of the model that allows parameterization of photoresponse (in development).

9. Chen, R-Z, M.G. Klein, C-F Sheng, Q-Y. Li, Y. Li, L-B. Li, and X. Hung. 2014. Mating disruption or mass trapping, compared with chemical insecticides, for Suppression of *Chilo suppressalis* (Lepidoptera: Crambidae) in Northeastern China. J. Econ. Entomol. 107:1828-1838.
-Adults occur from about mid-May to early October with irregular population peaks, causing consistent damage over the rice plants entire growing cycle.
-Jilan Province, Shuangyang County, Changchun, China

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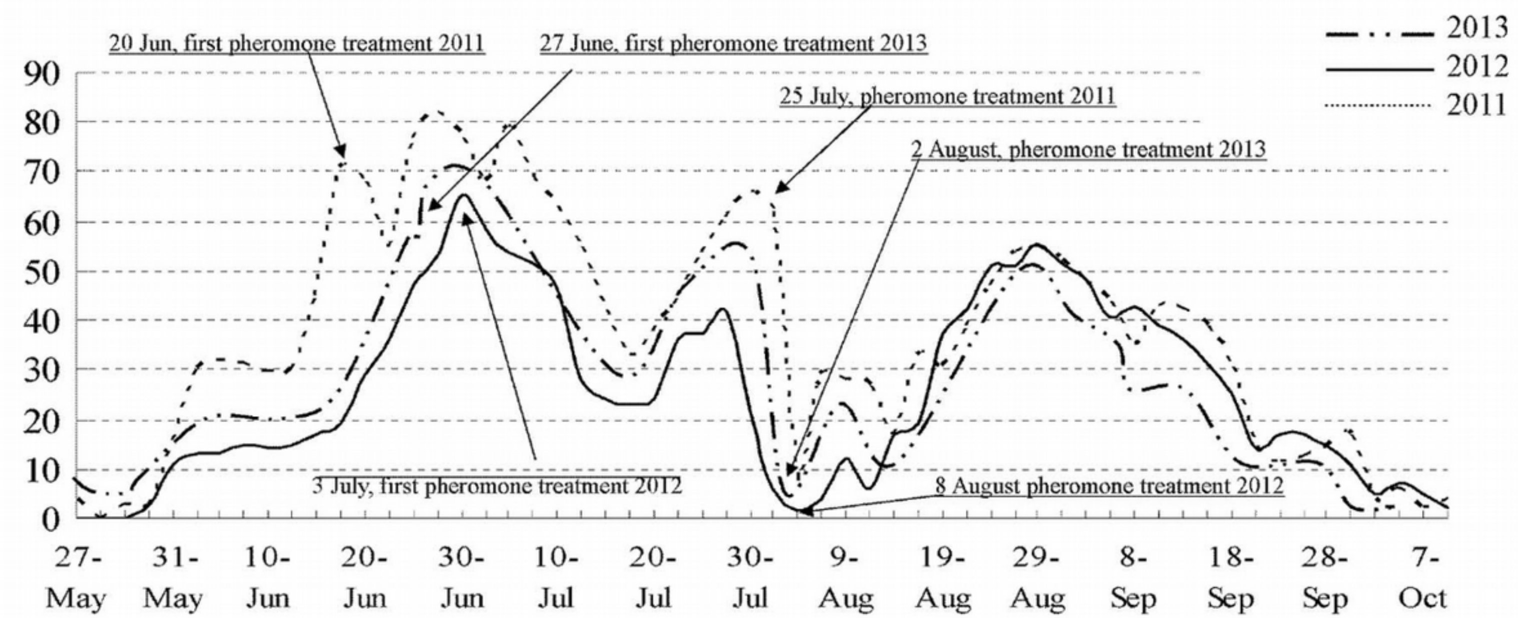


20 Jun, first pheromone treatment 2011

27 June, first pheromone treatment 2013

25 July, pheromone treatment 2011

2 August, pheromone treatment 2013

3 July, first pheromone treatment 2012

8 August pheromone treatment 2012

Fig. 1. Captures of *C. suppressalis* from pheromone traps in control plots, 2011–2012.

Methods: Estimate DD requirements for first, early, and subsequent moth peaks depicted in Fig. 1 using recent available data from degreedays.net

	OW generation							End-of-season
	First moths	early peak	late June pk	late July pk	late Aug pk	mid Sep pk.	late Sep pk.	DDs
2011	05/25/11	06/03/11	06/29/11	07/30/11	08/30/11	09/14/11	09/29/11	
2012	05/28/12	06/08/12	06/29/12	07/29/12	08/30/12	09/14/12	09/24/12	
2013	05/20/13	06/01/13	06/29/13	07/26/13	08/30/13	09/14/13	09/26/13	
Average	05/24/00	06/04/00	06/29/00	07/28/00	08/30/00	09/14/00	09/27/00	10/15/00

Degree-days from degreedays.net (keep in mind estimates are low compared to single sine; these are simple avg DDs with a relatively high Tlow of 10C)

DDs ZYCC Changchun CN 43.90N									
2018	288	402	683	1126	1537	1657	1716	1758	
2019	268	357	613	1023	1425	1574	1644	1713	
2020	184	275	580	971	1380	1487	1576	1608	
DDs 54157 Siping CN 43.18N									
2018	310	428	724	1173	1601	1725	1784	1823	
2019	277	375	654	1058	1470	1616	1694	1765	
2020	203	293	607	993	1403	1520	1608	1650	
DDs 50949 Qianguo CN 45.08N									
2018	294	415	722	1177	1599	1722	1790	1834	
2019	256	350	637	1055	1451	1602	1675	1741	
2020	201	298	587	1002	1425	1540	1624	1652	
Averages 3 sites, 3 years									No. Gen.s
	253	355	645	1064	1477	1605	1679	1727	2.1
Diff “early peak” and “late July peak”:				709					
Diff “late June peak and “late Aug peak”:					832				
Diff “late July peak” and “late Sep peak”:							615		

Results:

1) Being a temperate continental climate at 45N latitude, this season long trapping record probably reflects a similar trapping season for many U.S. localities.

The “end of season” (Oct 15) DDs averaged 1727/807=2.1, allowing for barely 2 generations but most likely one and a partial second generation before diapause occurs.

2) “First moths”, “early peak” and “late June peak” moths were estimated from this analysis at ca. 253, 355 and 645 DD after Jan 1.

3) There is a potential smaller generation spanning the “early peak” and “late July peak” interval with 709 DD, which could occur with higher quality hosts in the springtime (also: these are simple average DDs which UNDER estimate DDs in the spring and fall).

The interval between “late July peak” and “late Sep. peak” is 615, which perhaps supports the idea that a partial second generation can occur at least during warm years.

4) The main activity appears to be represented between “late June peak” and “late Aug. peak”, estimated as 832 DD, which matches well with the above-estimated generation time of 807 DD.

10. Summary of two studies having springtime emergence data:

As indicated above, DDs determined by temperature alone will not successfully represent the first and peak moth flight times in different latitudes where local populations will be selected towards optimal critical photoperiods (or perhaps by host crop phenology). Therefore, we will estimate spring flight conservatively by averaging values from the earliest Japanese population, and the 44N Chinese population:

	First moths	Peak moths
Omagari, Japan (39.5N)	165	356
Changchen, China (44N)	253	355
Average:	209	355
Value used:	200	360

Results: earliest first moths was rounded down from 209 to 200 DD, first peak moths averaged 355 DD (rounded up to 360 DD). These estimates could be improved by using a separate model to estimate biofix, model to estimate biofix, perhaps using a lower threshold temperature, or more likely, by using a photoperiod response function that has been developed, but not yet incorporated, into the current production version of DDRP.

Phenology Model Summary:

Stage Durations	**Deg. C**	**Deg. F**	**Notes**
Tlow	10.0	50	
Thi	38.0	100	based on immature development slowing at 34-35 C
	DD (C)	**DD (F)**	
Eggs	103	185	
Larvae	520	935	
Pupae	125	225	
Egg-to-adult	728	1310	
Pre-OV to 50% OV	79	143	
Egg to 50% OV, generation time	807	1453	

Model for uspest.org/dd/model_app (single sine method, start date Jan. 1)

Event	**DD (C)**	**DD (F)**
First OW larvae pupate in spring	75	135
First moths from OW larvae	200	360
Peak OW moths	360	648
First 1st gen. moths	1007	1813
Peak 1st gen. moths	1167	2101
First 2nd gen. moths	1814	3265
Peak 2nd gen. moths	1974	3553
First 3rd Gen moths	2621	4718
Peak 3rd gen. moths	2781	5006
First 4th gen. moths	3428	6170
Peak 4th gen. moths	3588	6458

Event Ranges for Degree-Day lookup table Maps (same thresholds)

	DDC		**DDF**	
Event	**(begin)**	**(end)**	**(end)**	**(begin)**
Pre-first moths	0	199	0	358
OW gen. flight activity	200	1,006	360	1,811
1st gen. flight activity	1,007	1,813	1,813	3,263
2nd gen. flight activity	1,814	2,620	3,265	4,716
3rd gen. flight activity	2,621	3,427	4,718	6,168
4th gen. flight activity	3,428	4,428	6,170	7,970

DDRP OW Parameters:		**DDC**	**Notes**
distro_mean	average DDs to OW larvae first pupation	235	Base on peak OW flight minus pupal devel. time
distro_var	variation in DDs to OW larvae first pupation	5000	
xdist1	minimum DDs (°C) to OW larvae first pupation	75	Based on first OW flight minus pupal devel. time
xidst2	maximum DDs (°C) to OW larvae first pupation	550	Based on slightly skewed normal population spread
distro_shape	shape of the distribution	normal	

Climate Suitability Model

Note: no previous climatic suitability modeling studies except for a Maxent study in Iran (Jalaeian et al. 2017 - see Source 19 below)

Sources of data for CLIMEX model fitting

11. Atapour, M. and S. Moharramipour. 2009 Changes of cold hardiness, supercooling capacity, and major cryptoprotectants in overwintering survival of *Chilo suppressalis* (Lepidoptera: Pyralidae). Environ. Entomol. 38:260-265.

- Studied supercooling point, survival at low temps, and sugar contents during diapause phases
- Study conducted on larvae that were collected from northern Iran (Gilan and Mazandarn provinces)
- Ambient temps lowest in Jan/Feb (4.4/3.7C) when larvae at highest diapause intensity and had high cold tolerance at -10, -15 and -20C
- Glycerol, a major cryptoprotectant, peaked in January
- During coldest months, supercooling points increased (around -11C) and larvae could survive below SCP values (i.e. they are freeze tolerant)
- Experience two to three generations, diapause induction occurrs in Sept, ends in March, and begin pupation in April
- Main result: larvae could survive -20C only in Dec, Jan and Feb because of increased cold hardiness that is associated w/ diapause

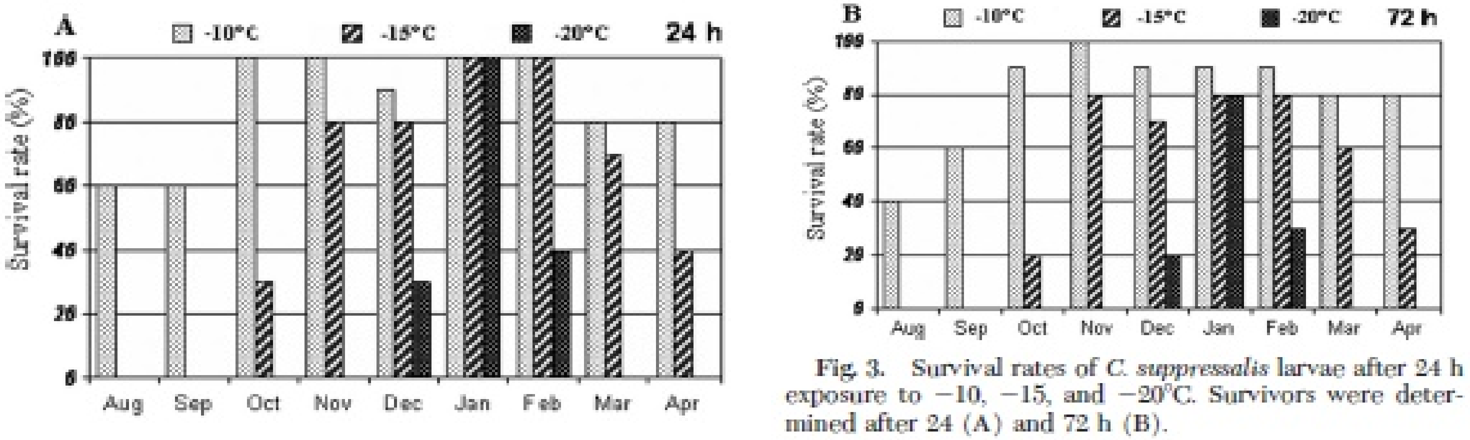


Fig. 3. Survival rates of *C. suppressalis* larvae after 24 h exposure to −10, −15, and −20°C. Survivors were determined after 24 (A) and 72 h (B).

12. Xiao, H., J. Chen, L. Chen, C. Chen and S. Wu. 2017. Exposure to mild temperatures decreases overwintering larval survival and post-diapause reproductive potential in the rice stem borer *Chilo suppressalis*. J. Pest. Sci. 90:117-125.

- Exposed overwintering larvae to temp treatments of 1, 5, and 10 C and at natural conditions w/ mean temp of 9.3C for 5-6 months
- Compared survival rates and body weights of OW larvae, diapause termination, and post-diapause reproductive potential
- Lower temps (1 and 5C) were better for survival than 10C and increased post-diapause reproduction potential in the following year
- Treatment of 5C results in highest pupation rate

13. Kisimoto, R. and V.A. Dyck. 2013. Climate and rice insects. *In* Proceedings of the Symposium on Climate and Rice. Pp. 367-391.

- They compared the climatic tolerances and northern range limits of some rice insects
- ASRB is found farther north then yellow rice borer, up into Hokkaido and northeast China (lat = 45N) [however, note ASRB locality records even farther north in Source 20]
- In southern (tropical) parts of range it is primarily a pest at higher elevations
- There are 3 geographical ecotypes: Shonai (northern, shorter life cycle, mild diapause), Saigoku (SW Japan), and Tosa (Kochi, subtropical)

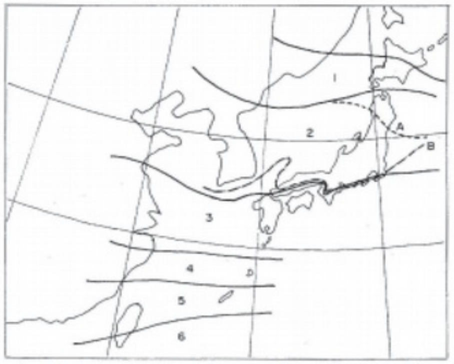
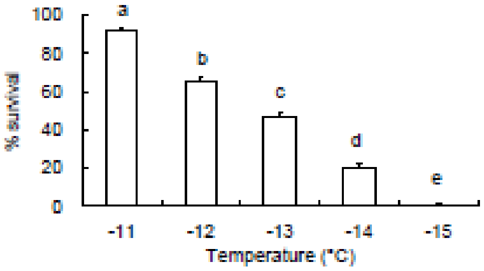
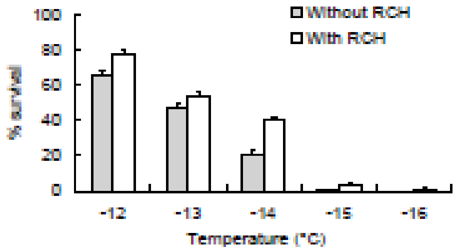


Fig 1: Isodevelopmental zonation of C. suppressalis
and the northern limiting line of the yellow rice borer (B).
A shows the practical border line of one generation life cycle.

14. Yang, G., J. Wen, Y. Han, and M. Hou. 2018. Rapid cold hardening confers a transient increase in low temperature survival in diapausing *Chilo suppressalis* larvae. Insects 9:53. doi:10.3390/insects9020053

- OW larvae avoid freezing by supercooling; progressively decreasing temps and diapause conribute to this capacity
- Tested diapausing larvae for a rapid cold hardening (RCH) response and role in surival at sub-zero temps
- Larvae exposed to a series of sub-zero temps (-11, -12, -13, -14 and -15C) for 2 hrs in climate chambers
- 21% of insects surived when transferred from 25C to -14C for 2 hrs
- 41% of insects survived when allowed to acclimate for 4 hr at 5C before 2hr exposure to -14C, indicating cold hardening
- The low rates of survival in general are because the larvae went from 25C to sub-zero temps abruptly; e.g. a sudden cold event in nature in fall or early spring





15. Cho, J.R., J.S. Lee, J.J. Kim, M. Lee, H.S. Kim and K.S. Boo. 2005. Cold hardiness of diapausing rice stem borer, *Chilo suppressalis* Walker (Lepidoptera: Pyralidae). J. Asia-Pacific Entomol. 8:161-166.

- Investigated super cooling point (SCP), cold hardiness and glycerol content in larvae from field in Taean, South Korea
- Lab-reared larvae pre-treated at 0C for 1h or 2h had increased survival at -10C
- SCP changed seasonally w/ large decrease towards Februrary
- Data presented in Table 1 showed 90-100% survival of larvae that were collected in field at various winter dates and exposed to -10C
- Results are consistent w/ other studies and show that the species can clearly survive -10 temps very well when given time to cold harden and it's in diapause

16. Tsumuki, H. and M. Hirai. 2007. Effects of photoperiod and temperature on endogenous ice nucleus production in larvae of the rice stem borer, *Chilo suppressalis* Walker (Lepidoptera: Pyralidae). Appl. Entomol. Zool. 42:305-308.

- Estimated the effects of photoperiod and temp on ice nucleus production
- Raised larvae at 25C under different photoperiods and different levels of acclimation to low temps
- Crystallization temp of whole bodies of non-diapausing and diapausing insects were -4C to -8.5C during cold vs. non-acclimation
- The crystallization temp muscle and epidermis of diapausing larvae rose to -11C after 9 days of cold acclimation at 5C (45 d after hatching)
- Tsumuki and Konno (1991, Cryobiology 28:376-381) showed that the crystallization temp of OW larvae collected in midwinter was below -17C
- Thus nondiapausing mature larvae can survive freezing but have a lower limit (-10C) than diapausing insects

17. Cui, Y., Y. Du, M. Lu and C. Qiang. 2011. Antioxidant responses of *Chilo suppressalis* (Lepidoptera: Pyralidae) larvae exposed to thermal stress. J. Therm. Biol. 36:292-297.

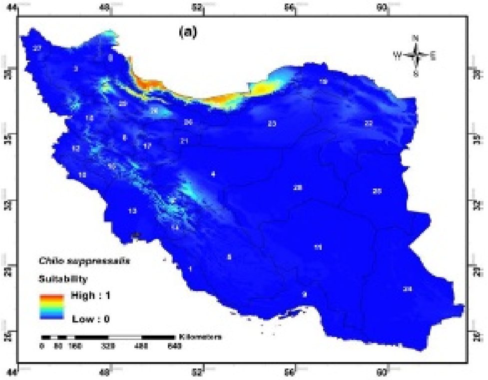
- Studied effects of thermal stress on expression of heat shock proteins (Hsp70), activity of antioxidant enzymes, and apoptosis in hemocytes in larvae
- Experimental groups were 30 5th instar larvae raised 28C (80% RH) and then exposed to 33, 36 or 39C for 2 hrs (control groups was kept at 28C)
- Found no significant difference in HSP expression at insects raised at 33, 36 and 39C but all three were significantly higher than control
- Found significant increase in activity of antioxidant enzyme SOD at 36C and 39C, and maximum activity of ACT enzyme at 39C
- HSP expression at 33C is consistent with Source 2's result that development slows at 34C due to heat stress
- Increased enzyme activity also consistent with Source 2, which reported higher activity of CAT, POZ, and SOD at 34C compared to 24C

18. Goto, M., Y-P Li, and T. Honma. 2001. Changes of diapause and cold hardiness in the Shonai ecotype larvae of the rice stem borer, *Chilo suppressalis* Walker (Lepidoptera: Pyralidae) during overwintering. Appl Entomol. Zool. 36:323-328.

- Studied cold hardiness and diapause in 2 ecotypes in Japan ("Shonai" in north and "Saigoku" in south)
- Collected OW larvae from field in Shonai district of Yamagata Prefecture throughought winter in 1995-1996
- All larvae that were collected in Dec and Jan survived 24h exposure to -15C, showing cold hardiness, which is consistent w/ other studies
- The Shonai ecotype had a shorter diapause duration than the Saigoku ecotype, terminating after the cold season in Feb whereas Shonai terminates in Nov
- They also differ in their cold hardiness characteristics

19. Jalaeian, M., A. Golizadeh, A. Sarafrazi, and B. Naimi. 2017. Inferring climate control of rice stem borer's spatial distributions using maximum entropy modelling. J. Appl. Entomol. 142:388-396.

- Used 195 occurrence records (presence only) and correlative niche modelling with Maxent to estimate suitability in Iran
- Northern areas were most suitable, consistent with the known distitribution of the species
- However their model is almost certainly overfitted: rice is almost exclusively grown along Caspian Sea, and all locality data came from there
- Precipitation had the highest contribution (66%) in the model (mostly bio14, precipitation of driest month = 51.7%)



Mean habitat suitability over 10 replicates

20. Locality records for fitting a CLIMEX model

Sources of data for locality records used for model fitting

1. GBIF.org (01 August 2020) GBIF Occurrence Download https://doi.org/10.15468/dl.5bpbub
2. Locality records from the literature:

Region	Country	Source	Notes
Europe	Hungary	Szeoke 2006 Folia Ent Hung 67:85-88	

	Spain	Vacas Gonzalez et al. (2016) J Asia-Pacifica Entomol 19:253-259	
	Russia	Poltavsky and Artokhin (2015) SHILAP Revta Lepid 43:461-465	
East Asia	Bangladesh	Rahaman et al. (2014) J Bangladesh Agril Univ 12:267-272	
	China	Chai and Du (2011) Ann Entomol Soc Am 104:998-1004	
		Chen et al. (2014) J Econ Entomol 107:1828-1838	
		Fu et al. (2016) J Therm Biol 61:115-118	
		He et al. (2013) J Econ Entomol 106:1832-1837	
		Huang et al. (2018) Ecol Evol 24:12694-12701	
		Lu et al. (2017) Crop Prot 100:196-202	
		Meng et al. (2008) Mol Ecol 17:2880-2897	
		Quan et al. (2016) Ecol Evol 6:4478-4487	
		Tang et al. (2014) Agr Sci Tech 15:843-845	Furthest north locality (Keshan)
		Wei et al. (2019) J Econ Entomol 112:1348-1353	
		Yao et al. (2016) Pest Manag Sci 73:1169-1178	
		Zhong et al. (2017) Sci Rep 7:13778	
	India	Rao and Nagaraja (1965) Proc Indian Acad Sci 63:175-217	
	Japan	Goto et al. (2001) Appl Entomol Zool 36:323-328	
		Kishino (1974) Japan Agricultural Research Quarterly 8:72-77	
		Xiao et al. (2017) J Pest Sci 90:117-125	
	South Korea	Park and Hyun (1990) Korean J Appl Entomol 29:257-268	
		Park et al. (2019) Mitochondrial DNA 4:850-851	
	Tawain	Tsumuki et al. (1994) Europ J Entomol 91:477-479	
Oceania	Australia	Li et al. (1990) Int J Trop Insect Sci 11:535-539	
	Indonesia	Hattori and Siwi (1986) JARQ 20:25-30	
	Phillipines	Cuong and Cohen (2002) Bull Entomol Res 92:265-268	
Middle East	Iran	Atapour and Moharramipour (2009) Env Entomol 38:260-265	
		Jalaeian et al. (2018) J Appl Entomol 142:388-396	
		Shamakhi et al. (2018) J Insect Sci 18:1-11	
		Toorani et al. (2019) Archives Phytopath Plant Prot 52:1079-1094	
	Pakistan	Karim and Riazuddin (1999) Pak J Biol Sci 2:261-276	Hottest localities

20. CLIMEX model (this study)

- Used locality data from GBIF and the literature to help with model fitting (see below)
- Experimented with irrigation settings because rice is a heavily irrigated crop in many regions, at least in dry season
- Hottest and cold localities where species occurs were used to calibrate heat and cold stress thresholds and rates
- The final parameters are below, with additional explanations following this table

Final CLIMEX parameters

Temperature Index

DV0	DV1	DV2	DV3
10	20	28	34

Cold Stress

TTCS	THCS	DTCS	DHCS	TTCSA	THCSA
-20	-0.0008	0	0	0	0

Heat Stress

TTHS	THHS	DTHS	DHHS
37	0.0001	0	0

Dry Stress

SMDS	HDS
0.15	-0.005

Wet Stress

SMWS	HWS
5	0.001

Day-degree accumulation above DV0

DV0	DV3	MTS
10	34	7

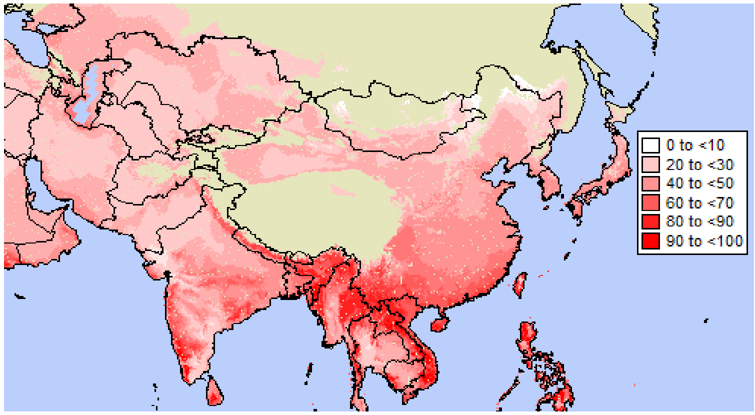
Degree-days per Generation

PDD
807

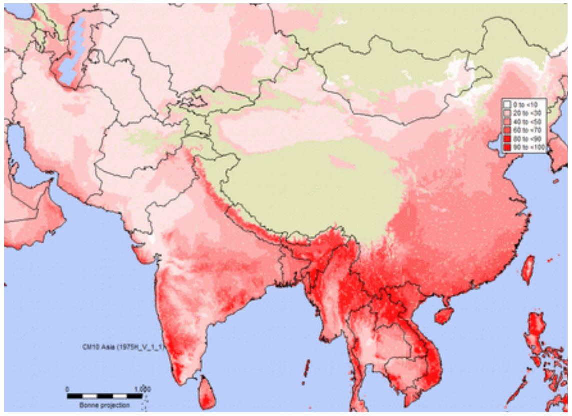
Irrigation scenario

- According to Guera et al. 1998 ("Producing more rice with less water from irrigated systems", https://ageconsearch.umn.edu/record/287568/files/Guera.pdf), 700 to 1,500 mm of water is used under traditional practices in medium- to heavy-textured soils in the Asian tropics and subtropics
- At least in wetter countries, most irrigation would occur during the dry season, but wet season irrigation may still occur (e.g. to soak land at the start of wet season)
- A topup irrgiation scenario for Winter = 3 mm/day and Summer = 5 mm/day resulted in realistic predictions of suitability for the species
- More conservative scenarios were also tested but they tended to underpredict suitability in dry regions (see below)

Winter = 3 mm/day, Summer = 5 mm/day



Winter = 2 mm/day, Summer = 2 mm/day



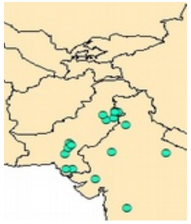
Temperature index parameters

- Lower and upper thresholds are 10C and 34C, respectively, as shown in the phenology model
- Source 2 (Shamakhi et al. 2018) reported that 24C was optimal for development, and no egg hatch occurred above 36C
- Set DV1 to 20 and DV2 to 28, which encompasses the potential range of optimal temperatures

Heat stress parameters

- Hottest localities were in Pakistan and western India
- Devel. studies and molecular studies show that the species may start to experience heat stress at ca. 34C (Cui et al. 2007, Shamakhi et al. 2018)
- However temperature experienced by insect (e.g. shelters, behavior) would be lower than air temp at a weather station
- Tested some lower values (e.g. TTHS = 37) but these may be too low, unless we assume a high rate of stress accumulation
- Using a heat stress threshold (TTHS) and rate (THHS) of 39C and 0.0004, respectively, resulted in the inclusion of most of the hotted localities (EI > 20)
- EI maps below were generated using the irrigation scenarios of Winter = 3 mm/day, Summer = 5 mm/day; and parameters as above but changing HS params
- **Areas w/ heat stress greater than approx 17 units may results in EI < 20 (low suitability)**

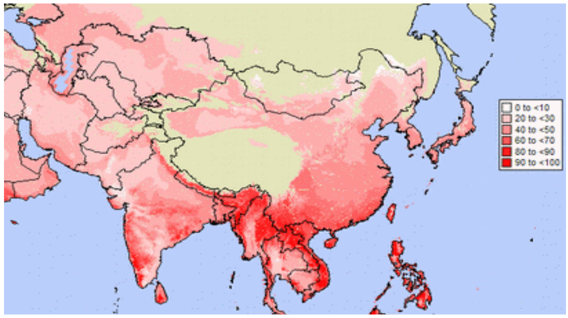
TTHS	THHS
39	0.0004

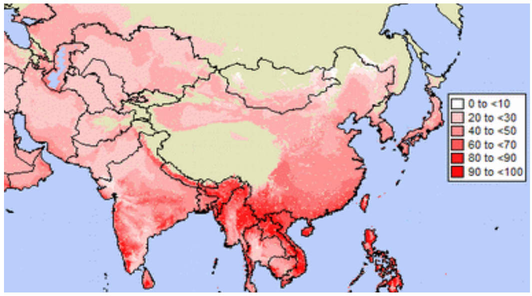


TTHS	THHS
37	0.0001

EI

HS





<u>Cold stress parameters</u>

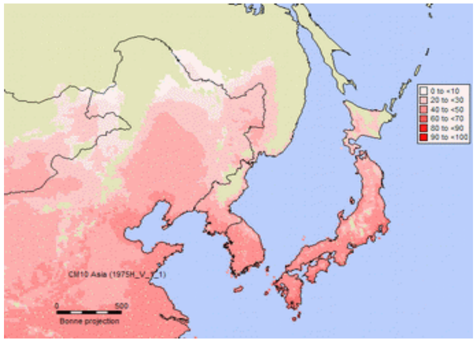
- Coldest locality was in Keshan County, China (the furthest north locality)
- Multiple studies show the species can survive very well at -10C if it is allowed to build up cold hardiness
- Using a cold stress threshold (TTCS) and rate (TCHS) of -20C and 0.0007, respectively, produced EI > 20 at Keshan and excluded farther north areas (see below)
- A TTCS of -20C is supported by exerpimental data presented by Atapour and Moharramipour (2009)[Source 11]
- Lower TTCS values were tested but it predicted suitable conditions farther north, and the species does not occur farther noth than Keshan according to the literature
- EI maps below were generated using the irrigation scenarios of Winter = 3 mm/day, Summer = 5 mm/day; and parameters as above but changing cold stress params
- Areas w/ cold stress greater than approx 30 units have EI < 20 (low suitability)

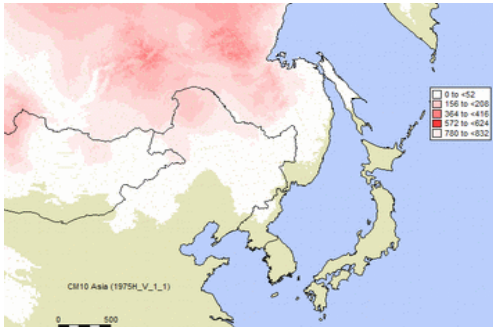
TTCS	THCS
-20	-0.0007

Keshan is included in area where
EI > 20 but other northern areas are
not, consistent w/ known distribution

EI

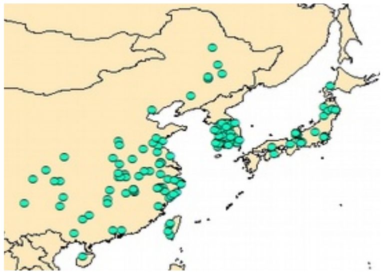
CS

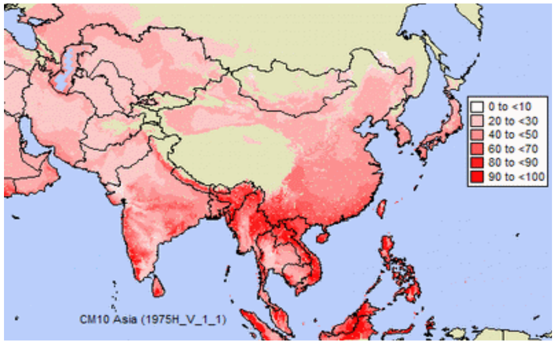


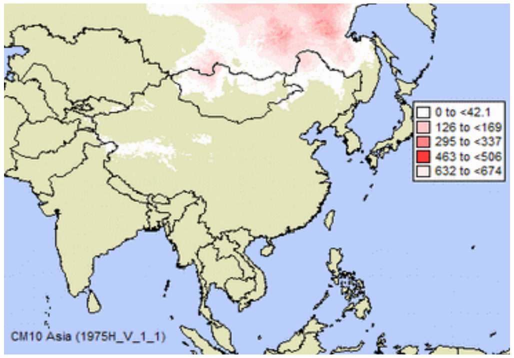


TTCS	THCS
-25	-0.0008

Suitability predicted farther north than northernmost locality; too liberal

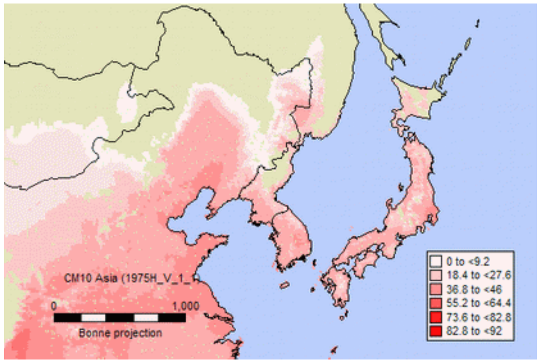


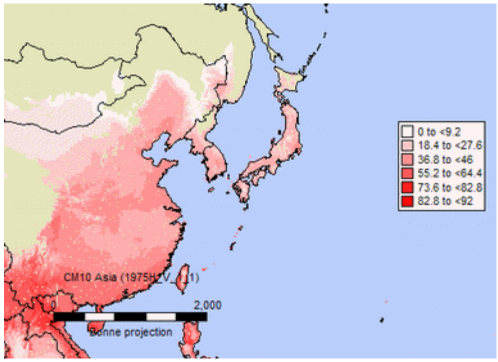




TTCS	THCS
-20	-0.004

Keshan excluded; too stringent



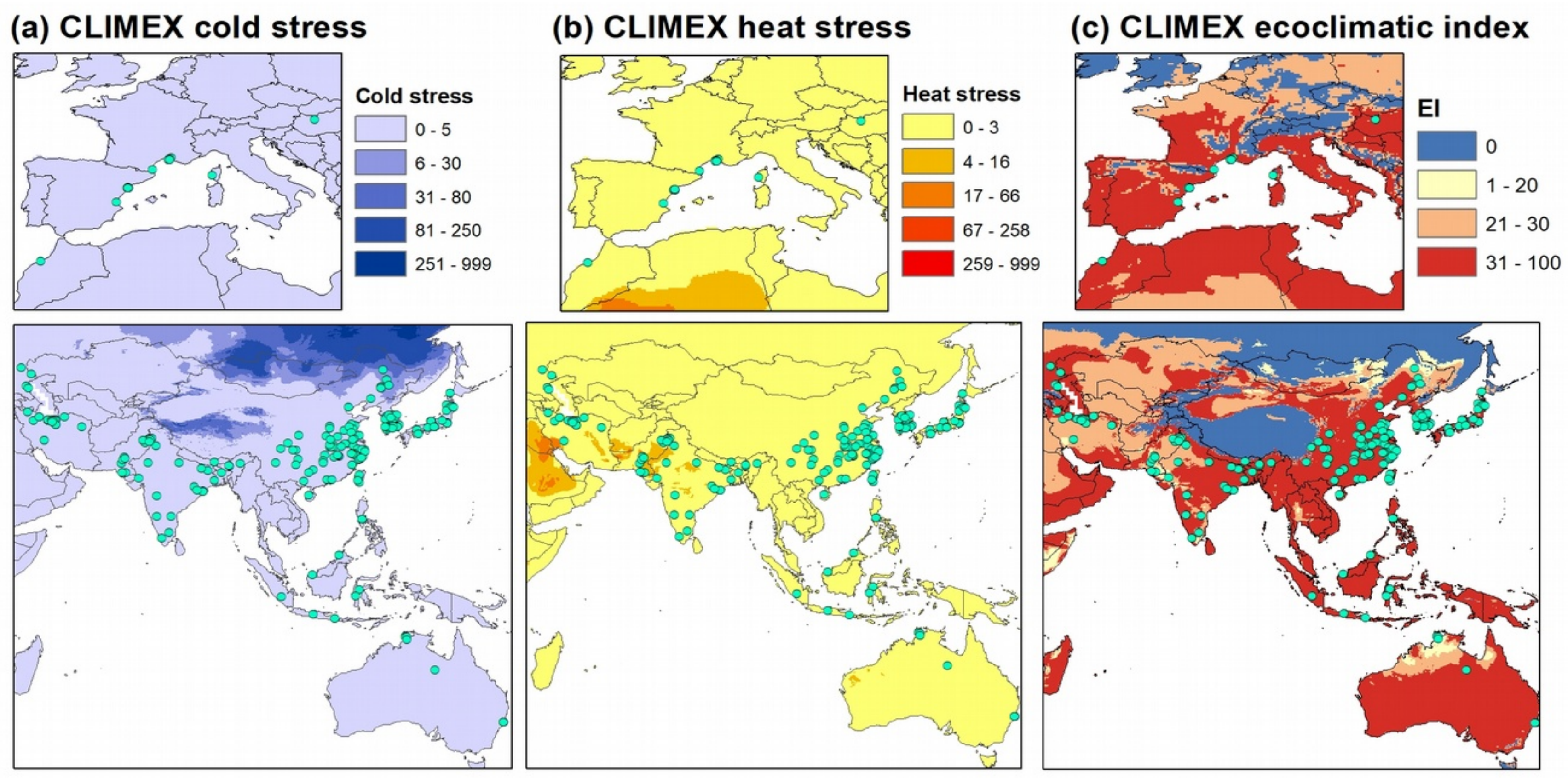


<u>Moisture index and stress (wet/dry) parameters</u>

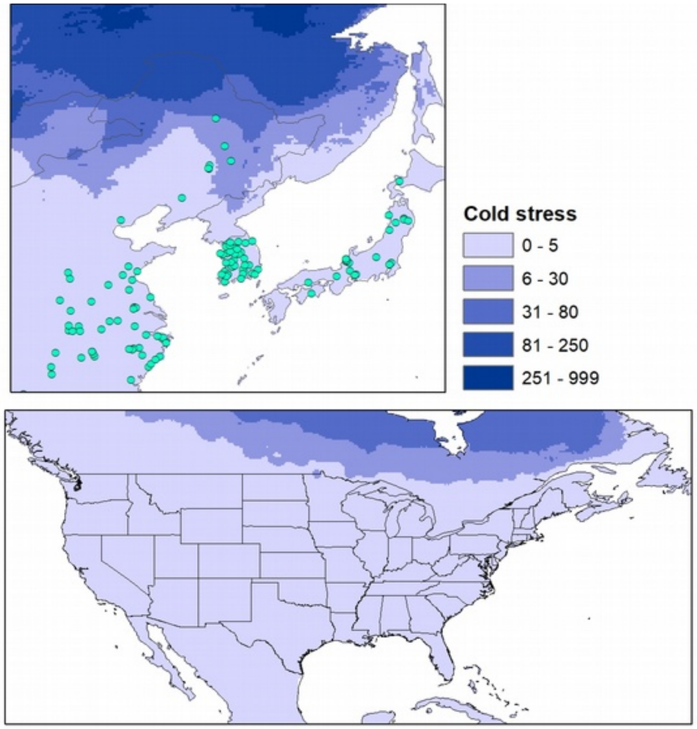
- Rice grows well in waterlogged conditions, so upper optimal moisture index values were set high (DV3 = 3.5; DV4 = 7)
- More data are needed to better calibrate moisture index and moisture stress values

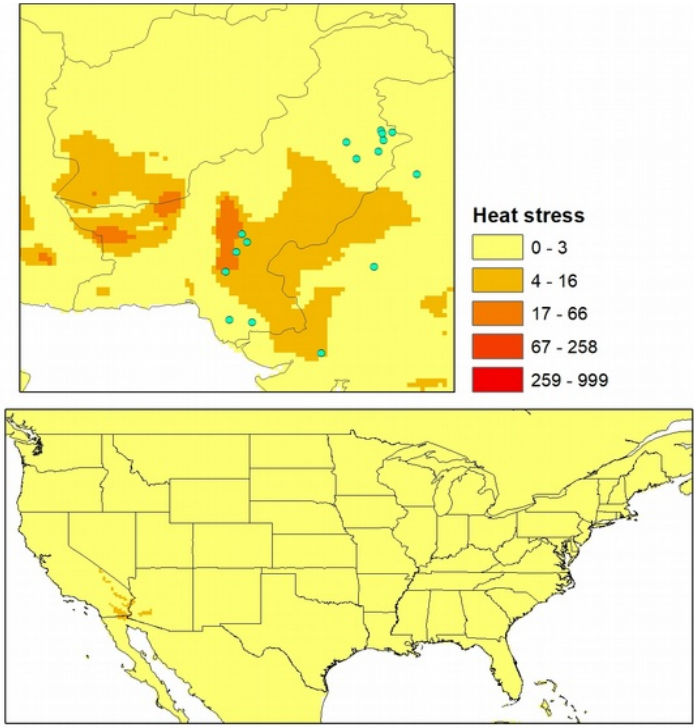
CLIMEX maps of cold stress, heat stress, and the ecoclimatic index for Europe, Asia, and Oceania

- ca. 90% of localities have EI >= 30
- Cold and heat stress lowers EI values in coldest (northern China) and hottest areas (Pakistan/western India), but they are still above 20
- Suitability in Hokkaido Island in Japan is on East side, consistent with known distribution (Morimoto et al. 1998, Appl Entomol Zool 33:147-155)
- Highest suitability in Iran (EI > 30) is along Caspian Sea, which is consistent with the Maxent model of Jalaeian et al. (2017)



CL
- A
- C
- H

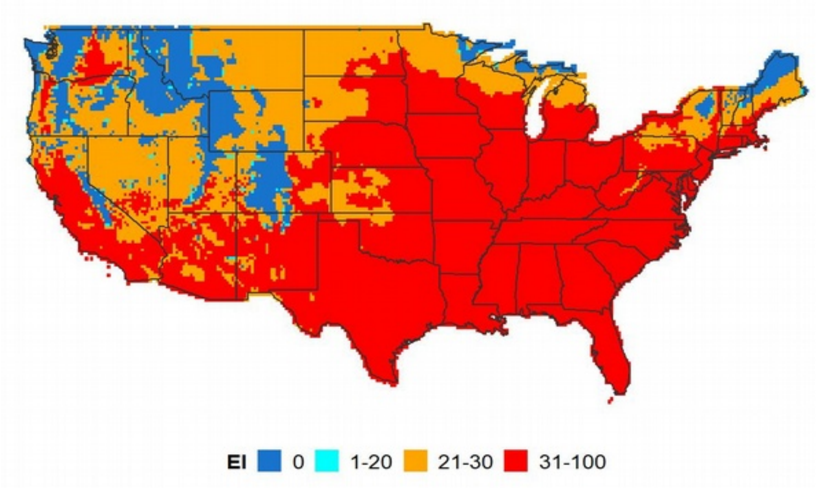




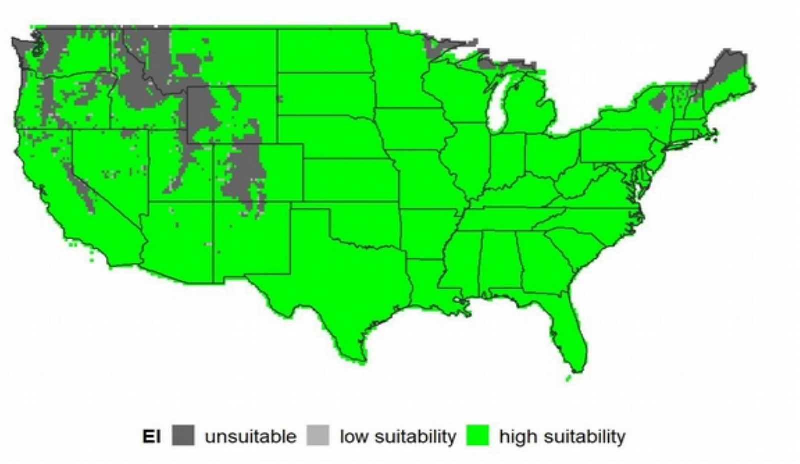
CLIMEX Ecoclimatic Index for CONUS

- Note that areas deemed to be unsuitable (mostly in the Rocky Mountains region) are due to insufficient degree day accumulation, not cold stress
- Areas in the East (below approx. lat = 46N) and Southwest may be the most suitable because EI values are greater than 30

Four categories (assume EI > 20 is suitable; EI > 30 is most suitable)



Three categories (assume that species could establish where EI > 20)

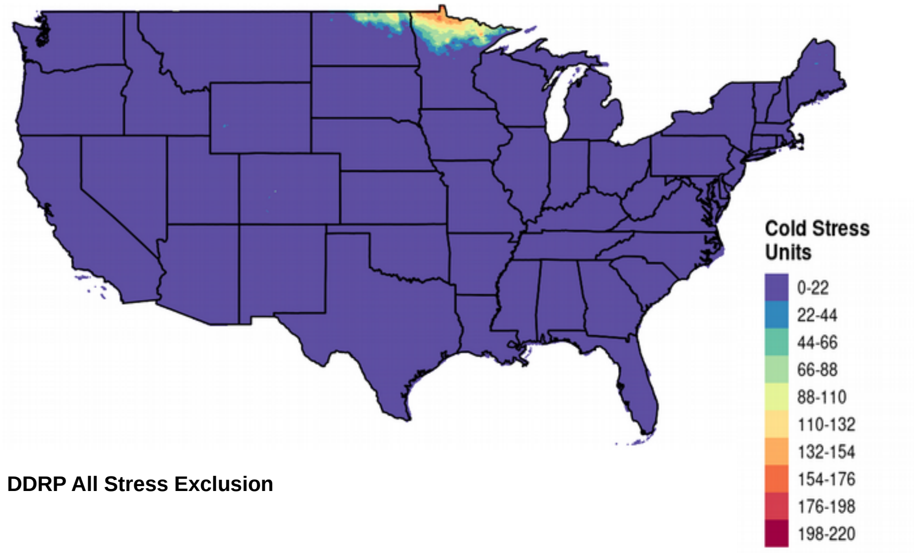


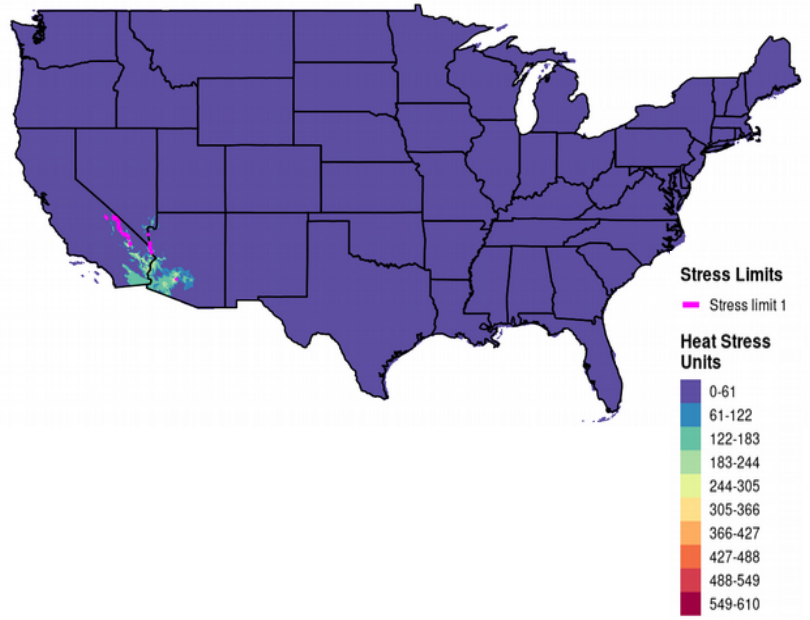
20. DDRP climate suitability model (this study)

- Analysis used daily downscaled 1961-1990 normals to match time scale of CLIMEX
- Calibrating according to CLIMEX is difficult because stress limits appear to be outside of CONUS, as shown above
- Set moderate and severe cold stress limits to 400 and 800 units, which is ca. 2X and 4X higher than the highest cold stress experienced in CONUS, respectively
- This scaling is consistent with CLIMEX results - i.e. the species needs ca. 5X more cold stress to be excluded in the coldest part of CONUS (northern MN)
- Set moderate heat stress limit to 250, which resulted in moderate stress in a tiny part of CONUS where heat stress in CLIMEX was highest, and the severe heat stress limit to 750, which is slightly higher than the highest level found in CONUS (610 units)
- Thus, heat stress is not high enough anywhere to completely exclude the species, consistent with CLIMEX

DDRP Cold Stress	Value	Units
cold stress threshold	-20	C
limit 1 (mod. cold stress)	400	DDC
limit 2 (sev. cold stress)	800	DDC

DDRP Heat Stress	Value	Units
heat stress threshold	39	C
limit 1 (mod. heat stress)	250	DDC
limit 2 (sev. heat stress)	750	DDC





DDRP All Stress Exclusion