Phenology/Degree-Day Model Analysis – Vers. 1, Aug. 11, 2020

by Brittany Barker and Len Coop for USPEST.ORG at Oregon State University, Oregon Integrated Pest Management Center

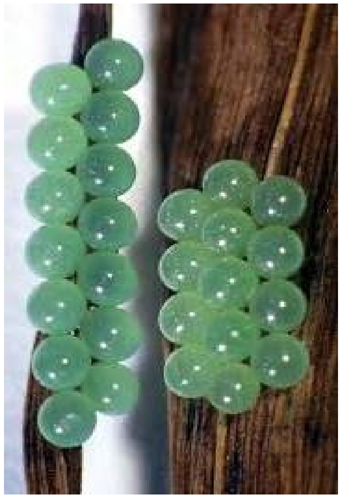
Sunn pest ***Eurygaster integriceps*** **(Puton)** **[Hemiptera: Scutelleridae]**

Native to central Asia in mountain and foothill territories of Transcaucasia, Iraq, Iran, Afghanistant and Tajikstan (Vavilov, 1926; 1964)

Hosts: Wheat, barley and oats

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

- The species has obligatory diapause and only generation a year (univoltine)
- It aestivates ("over-winters") as an adult during hot, dry months and is active to feed and lay eggs in the Spring for ~30 days
- New generation adults migrate to high altitudes for "over-wintering" except in high-latitude (cold) regions where they stay in cereal field
- Nymphs pass through four instars; for this model, the Pupae are represented by the Pre-Oviposition (Pre-OV) stage
- The species' biology is summarized in more detail below



Images from https://planthealthaustralia.com.au and https://mel.cgiar.org

Thresholds, degree-days and events used in Sunn Pest DDRP model:

Parameter abbr.	Description	degF	degC	DDF	DDC
eggLDT	egg lower dev threshold	54.0	12.22	-	-
eggUDT	egg upper dev threshold	96.8	36.0	-	-
larvaeLDT	larvae lower dev threshold	54.0	12.22	-	-
larvaeUDT	larvae upper dev threshold	96.8	36.0	-	-
pupaeLDT	pupae lower dev threshold	54.0	12.22	-	-
pupaeUDT	pupae upper dev threshold	96.8	36.0	-	-
adultLDT	adult lower develpmental threshold	54.0	12.22	-	-
adultUDT	adult upper dev threshold	96.8	36.0	-	-
eggDD	duration of egg stage in DDs	-	-	144	80
larvaeDD	duration of larva (nymph) stage in DDs	-	-	738	410
pupDD	duration of adult pre-OV (no pupal) stage in DDs	-	-	350	194
adultDD	duration of adult (through 30% OV) stage in DDs	-	-	550	306
Gen TimeDD	duration of full generation in DDs	-	-	1782	990
OWpupaeDD	DDs Jan 1 to 1st arrival of ovipositioning adults (no OW pupae)	-	-	180	100
eggEventDD	DDs into egg stage when hatching begins	-	-	164	91
larvaeEventDD	DDs into larvae stage when mid-larval development occurs	-	-	369	205
pupaeEventDD	DDs into preOV stage when adults becoume active	-	-	18	10
adultEventDD	DDs into adult stage when peak (30% OV) oviposition occurrs	-	-	201	112

Parameter abbr.	Description	degF	degC	DDF	DDC	
coldstress_threshold	cold stress threshold	-22.0	-30.0	-	-	
coldstress_units_max1	cold degree day limit when most individuals die	-	-	18	10	
coldstress_units_max2	cold degree day limit when all individuals die	-	-	45	25	
heatstress_threshold	heat stress threshold	104.0	40.0	-	-	
heatstress_units_max1	heat stress degree day limit when most individuals die	-	-	360	200	
heatstress_units_max2	heat stress degree day limit when all individuals die	-	-	720	400	
distro_mean	average DDs to emergence (spring arrival in fields)	-	-	378	210	Data lacking for peak or average arrival
distro_var	variation in DDs to emergence	-	-	3600	2000	
xdist1	minimum DDs (°C) to emergence	-	-	180	100	Based on several sources: #2, #7, #8.
xdist2	maximum DDs (°C) to emergence	-	-	630	350	This should reflect population spread
distro_shape	shape of the distribution	-	-		normal	

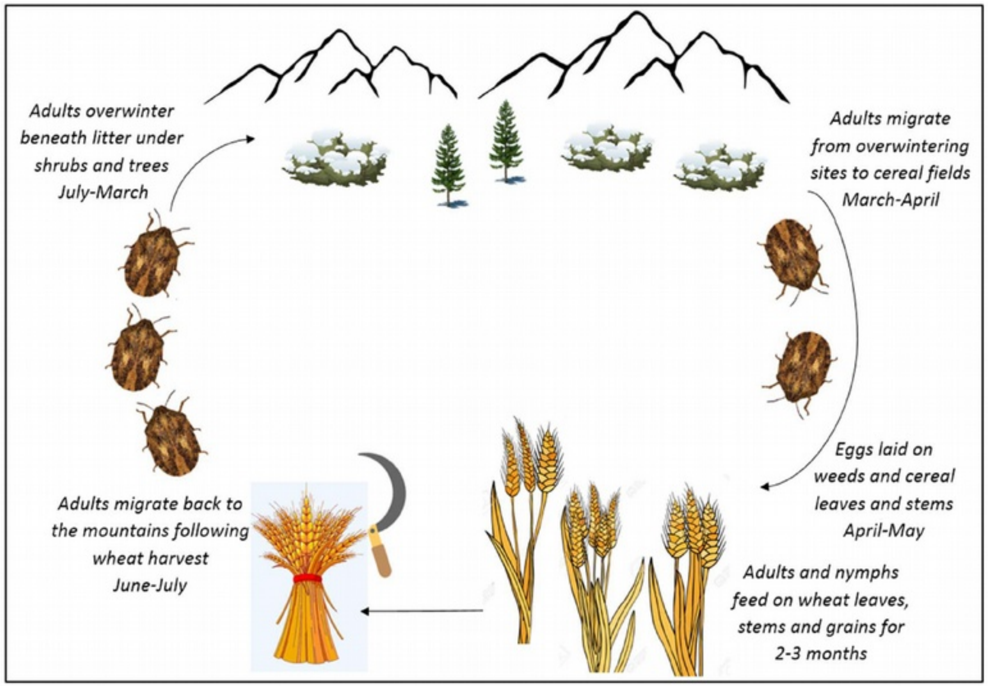
Degree-Day Model for USPEST.ORG:

	DDF	DDC
First arrival and egg-laying by OW adults in spring:	180	100
Peak egg-laying in spring:	378	210
Peak nymphs:	891	495
First adults:	1062	590
Peak adults (will leave fields to overwinter elsewhere):	1260	700

Biology of *E. integriceps*

- The biology of *E. integriceps* is reviewed in detail in:
  1) Brown. 1962. Researches on the ecology and biology of *Euryaster integriceps* Put (Hemiptera, Scutelleridae) in Middle East countries, with special references to the overwintering period. Bulletin of Entomological Research 53:445-514.
  2) Davari A and Parker BL. 2018. A review of research on Sunn Pest {*Eurygaster integriceps* Puton (Hemiptera: Scutelleridae)} management published 2004-2016. Journal of Asia-Pacific Entomology 21: 352-360.
  3) Critchley B. 1998. Literature review of Sunn pest *Eurygaster integriceps* Put. (Hemiptera, Scutelleridae). Crop Protection 17:217-287.
- "'Overwintering" period (inactive period, aestivation)
  - It is inactive during hot and dry months (~8 mos per year), in which it migrates to mountain areas ca. 1000 m above the invasion area, and shelters in tree and shrub litter
  - The resting (inactive) period is often referred to the "overwintering period"
  - In colder regions, diapausing insects remain in vicinity of cereal fields, but will migrate considerable distances in dry and moderate climates
  - During active months (4 mos in spring and early summer), it uses wind-aided dispersal to move to cereal fields (~10-20 km away from OW site)
  - Overwintered adults start flying at an average daily temperature of 12-14°C in spring, and flight activity is also influenced by humidity
  - The active period lasts ca. 30 days but it can be longer in areas with lower temps and frequent rains (reviewed in Davari and Parker 2018)
  - Over-wintering behavior can vary according to climatic conditions and geography (reviewed in Davari and Parker 2018)
  - The egg-to-adult process takes a minum of 35-37 days but could last as long as 50-60 days depending on food availability and field conditions (Critchley 1998)
  - Damp, cold, cloudy weather and high winds have adverse effects on population development and hence survival (Critchley 1998)
- Thermal limits
  - Max temps >30C in summer (July to Sept) were tolerated, as were min temps of -2.5 to -3C in the winter (Dec and Jan) (Brown, 1962)
  - If the insect is well fed it will resist frosts of about -30C, and mortality during such years did not exceed 20% of the wintering population (Radjabi, G. 1994. Appl. Entom. Pytopath. 61: 1-10)
  - Lab experiments showed "pathologic activity" of insects at temps from 37-48C before they died at 49.5C (see Source 9)

Fig. 1 of Davari and Parker (2018): Life cycle of Sunn pest.



Summary of data on temps when adult emergence from OW sites occurs

- Krasnodar Territory, Russia: 12C and when max temps reached above 20C [Shumakov and Vingradova 1958 (Source 7)]
- Syria: adults migrate to wheat fields when mean temps reached 14-15C (Oncuer & Ivan 1995; Critchley 1998)
- Aegean region in Turkey: adults emerged when mean temps were 9-10C (Sheick & A Rahbi 1996)
- Iran: Radjabi 2000 reported adults emerge when temps reach 13.5-14.3C, whereas Azad (2006) and Tafaghodinia & Majdabadi (2006)[Source 8] both reported temps in range of ~11.8-13.7C

Synthesis of results of the duration of life stages in DDCs

* Note that the PreOV stage will be treated as Pupae for this model, because the species has simple metamorphosis

Values in yellow are from addition/subtraction of other values

			(assumed 12.22C threshold)						
Stage	**Source 1**	**Source 6**	**Source 2**	**Src 3 -remove**	**Source 4**	**Source 5**	**Source 7**	**Source 9**	**Average**
Immature stages									
Egg	80	-	94		-	-	-	118	97
Nymphs	-	-	442		464	410		-	438
1st instar	-	-	-		64	-	48	-	56
2nd instar	-	-	-		120	120	-	-	120
3rd instar	-	-	-		89	76	-	-	83
1st - 3rd instar	-	-	214		274	196	-	-	228
4th instar	-	-	-		84	88	-	-	86
5th instar	-	-	-		109	126	-	-	117
Egg to adult emergence	-	-	536		561	507	-	-	536
Adult Stage		670							
PreOV + OV	-	566	-	-	-	-	-	-	
PreOV	-	194	-	-	-	-	-	-	
OV	-	372	-	-	-	-	-	-	
30% OV	-	112	-	-	-	-	-	-	

PreOV + 30% OV	-	306	-	-	-	-	-	-	
PostOV		104							
Full generation*		842	842		849	795			842

(note Full generation degree-days makes little practical sense as this species is univoltine and has a long aestivation/overwintering period)

Results: Removed Source three data as probably outliers due to poor temperature monitoring (much faster than expected development); using PreOV + 30% of OV period to estimate generation time. DDC requirements for eggs, nymphs, PreOV, OV, and PreOV+30% OV are: 97, 438, 194, 372, and 306.

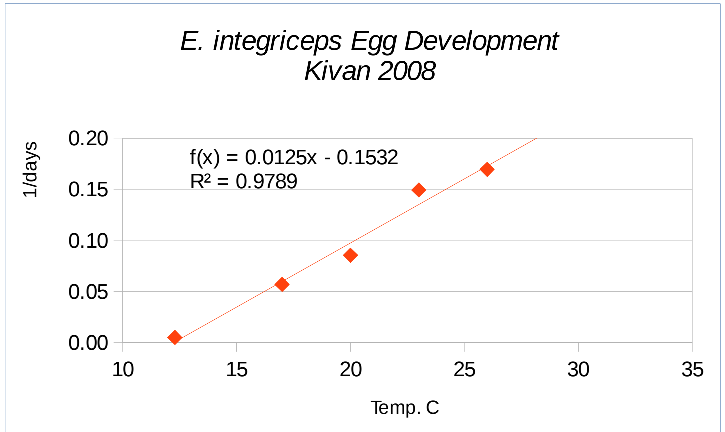
Source 1. Kivan, M. 2008. Development rate and lower temperature threshold in the eggs of *Eurygaster integriceps* (Heteroptera: Scutelleridae). Insect Science 15:163-166.

- Conducted a temperature-development lab study on sunn pest eggs at 17, 20, 23, 26 and 32C (+-1C)
- Egg development required 90.9 DDs above a threshold of 11.7C
- Their lower threshold is similar to several egg parasitoids of Sunn pest (*Trissolcus semistriatus*, *T. simoni*, and *T. rufiventris)*

Data from Fig. 1

Temp C	Duration (days)	Duration rate (1/days)
12.29	199	0.01
17	17.6	0.06
20	11.7	0.09
23	6.7	0.15
26	5.9	0.17
32	4.5	

slope:	0.0125
intercept:	-0.1532
R-sq:	0.9789
1/slope	80
-a/b	12.22



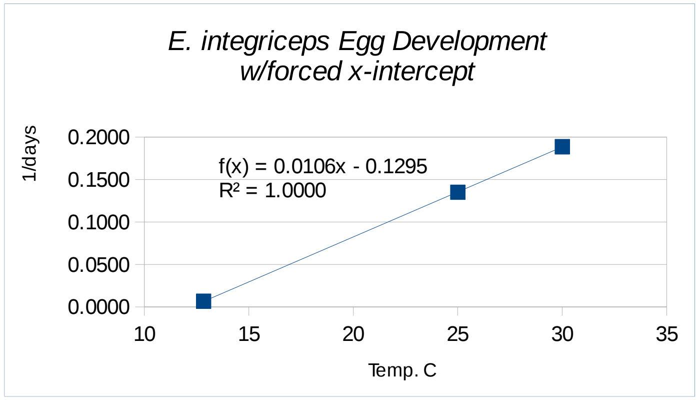
Source 2. Gözüaçik, C., A. Yiğit, and Z. Şimşek. 2016. Predicting the development of critical biological stages of Sunn Pest, *Eurygaster integriceps* Put. (Hemiptera: Scutelleridae), by using sum of degree-days for timing its chemical control in wheat. Turkish Journal of Agriculture and Foresty 40:577-582.

- Goal was to predict the critical biological stages in chemical control of Sunn pest
- Conducted study in climate chamber conditions and in 28 wheat fields in Adiyaman, Diyarbakir, and Sanlurfa provinces of Turkey from 2007 to 2010
- See below for estimates of degree-days
- Their estimates could provide better decision making of when to start pesticides when 1st and 4th nymph stages appear
- They derived development thresholds and thermal constants for eggs, nymph stages, and new generation adults
- Degree-days were calculated using the simple average formula
- The Sunn pest "culture" was started from 10 overwinterred adults (5 males, 5 females) collected on 23 March 2011 from Diyarbakir
- The experiment was set up w/ 10 replications and initiated w/ 10 fresh egg masses
- Unfortunately they only studied two temps: 25 and 30C
- Their estimate duration of egg stage was very similar to Kivan (2008): 93.2 DDCs vs. 90.9 DDCs
- Their estimates for the duration of nymph stages were very similar to those reported by Şimşek and Yilmaz (1992) (see Source 4):
- In analyzing Şimşek and Yilmaz's (1992) data with their method, they estimated a LDT = 12.61C and DDCs = 452.14 for all nymph stages (vs. their estimated LDT = 12.89C and DDCs = 422.61)
- Their results suggest that eggs and nymphs have very similar lower thresholds (eggs slightly lower)

Summary of Table 1:

Stage	Days Development 25C	30C	LDT (degC)	DDCs
Egg	7.4	5.3	12.4	93.2
1st - 3rd instar	20.8	14	14.7	214.2
1st - 5th instar	34.9	24.7	12.9	422.6
Egg - adult emrg.	45.1	31.6	13.3	527.7

	Eggs			Nymphs	
Temp C	1/days	Days	Temp C	1/days	Days
12.84	0.0067	150	13.28	0.0025	400
25	0.1351	7.4	25	0.0287	34.9
30	0.1887	5.3	30	0.0405	24.7
slope:	0.011			0.002	
intercept:	-0.130			-0.028	
R-sq:	1.000			1.000	
1/slope	94			442	
-a/b	12.22			12.22	



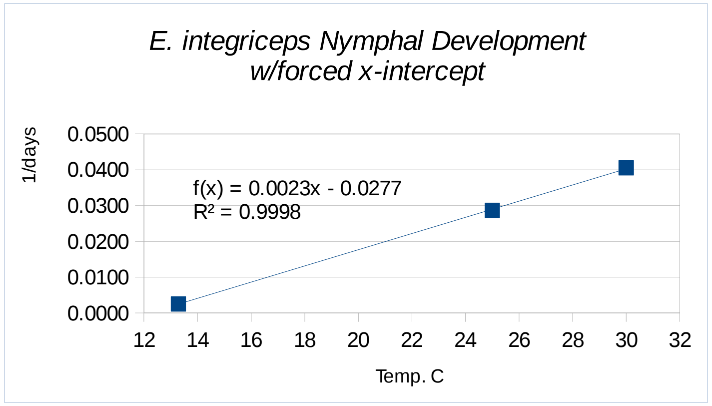


Table 2: Sum of degree-days (accumulation of effective temperature totals) starting from 1 January to observation dates for critical biological stages for chemical control of Sunn pest, *Eurygaster integriceps* Put., in wheat fields in Adıyaman, Diyarbakır, and Şanlıurfa provinces during 2007–2010.

(make minor adjustment for Tlow=12.89 used here vs. our Tlow of 12.2C)

Province	District	Date	Year	DDC	Event
Adıyaman	Merkez	30-Apr	2007	57.1	1st egg-laying
Diyarbakır	Ergani	6-May	2007	39.9	1st egg-laying
Şanlıurfa	Hilvan	-	2007		1st egg-laying
Adıyaman	Merkez	14-Apr	2008	67.5	1st egg-laying
Adıyaman	Kâhta	10-Apr	2008	35.1	1st egg-laying
Diyarbakır	Ergani	-	2008		1st egg-laying
Adıyaman	Merkez	23-Apr	2009	40.3	1st egg-laying
Adıyaman	Kâhta	24-Apr	2009	38.9	1st egg-laying
Diyarbakır	Ergani	3-May	2009	49.5	1st egg-laying
Şanlıurfa	Bozova	12-Apr	2010	30.8	1st egg-laying
Şanlıurfa	Hilvan	17-Apr	2010	33.9	1st egg-laying
Şanlıurfa	Siverek	22-Apr	2010	52.6	1st egg-laying
Adıyaman	Merkez	7-May	2007	72.2	1st emrg. of 1st-stage nymphs
Diyarbakır	Ergani	11-May	2007	83.5	1st emrg. of 1st instar nymphs
Şanlıurfa	Hilvan	10-May	2007	74.1	1st emrg. of 1st instar nymphs
Adıyaman	Merkez	20-Apr	2008	106.8	1st emrg. of 1st instar nymphs
Adıyaman	Kâhta	19-Apr	2008	91.1	1st emrg. of 1st instar nymphs
Diyarbakır	Ergani	24-Apr	2008	105.5	1st emrg. of 1st instar nymphs
Adıyaman	Merkez	9-May	2009	76	1st emrg. of 1st instar nymphs

1st egg-laying summary

Cross-check using degreedays.net Tlow=12C
LTAJ Gaziantep, Turkey 37 N. Latitude

Average Date	Degree-days: Sta LTAJ 2018	2019	2020	Avg
22-Apr	181	47	120	116

Range 1st egg-laying

	Earliest	Last
Date:	04/10/08	05/06/07
DDC:	30.8	67.5

Adıyaman	Kâhta	10-May	2009	79.8	1st emrg. of 1st instar nymphs
Diyarbakır	Ergani	11-May	2009	69	1st emrg. of 1st instar nymphs
Şanlıurfa	Bozova	30-Apr	2010	90	1st emrg. of 1st instar nymphs
Şanlıurfa	Hilvan	3-May	2010	92	1st emrg. of 1st instar nymphs
Şanlıurfa	Siverek	4-May	2010	72.6	1st emrg. of 1st instar nymphs
Adıyaman	Merkez	12-May	2007	118.3	1st emrg. of 2nd instar nymphs
Diyarbakır	Ergani	16-May	2007	125.7	1st emrg. of 2nd instar nymphs
Şanlıurfa	Hilvan	14-May	2007	104.1	1st emrg. of 2nd instar nymphs
Adıyaman	Merkez	26-Apr	2008	145.4	1st emrg. of 2nd instar nymphs
Adıyaman	Kâhta	24-Apr	2008	138.7	1st emrg. of 2nd instar nymphs
Diyarbakır	Ergani	4-May	2008	133.5	1st emrg. of 2nd instar nymphs
Adıyaman	Merkez	13-May	2009	96.1	1st emrg. of 2nd instar nymphs
Adıyaman	Kâhta	15-May	2009	113	1st emrg. of 2nd instar nymphs
Diyarbakır	Ergani	18-May	2009	127	1st emrg. of 2nd instar nymphs
Şanlıurfa	Bozova	6-May	2010	117	1st emrg. of 2nd instar nymphs
Şanlıurfa	Hilvan	10-May	2010	138.4	1st emrg. of 2nd instar nymphs
Şanlıurfa	Siverek	11-May	2010	122.1	1st emrg. of 2nd instar nymphs
Adıyaman	Merkez	24-May	2007	212	1st emrg. of 4th instar nymphs
Diyarbakır	Ergani	30-May	2007	273	1st emrg. of 4th instar nymphs
Şanlıurfa	Hilvan	23-May	2007	191.7	1st emrg. of 4th instar nymphs
Adıyaman	Merkez	12-May	2008	209.7	1st emrg. of 4th instar nymphs
Adıyaman	Kâhta	3-May	2008	198.1	1st emrg. of 4th instar nymphs
Diyarbakır	Ergani	20-May	2008	199.5	1st emrg. of 4th instar nymphs
Adıyaman	Merkez	-	2009	-	1st emrg. of 4th instar nymphs
Adıyaman	Kâhta	23-May	2009	209.5	1st emrg. of 4th instar nymphs
Diyarbakır	Ergani	-	2009	-	1st emrg. of 4th instar nymphs
Şanlıurfa	Bozova	21-May	2010	260.8	1st emrg. of 4th instar nymphs
Şanlıurfa	Hilvan	22-May	2010	252.3	1st emrg. of 4th instar nymphs
Şanlıurfa	Siverek	24-May	2010	224.8	1st emrg. of 4th instar nymphs
Adıyaman	Merkez	7-Jun	2007	362.8	1st emrg. of new adults
Diyarbakır	Ergani	7-Jun	2007	372.3	1st emrg. of new adults
Şanlıurfa	Hilvan	30-May	2007	270	1st emrg. of new adults
Adıyaman	Merkez	21-May	2008	274.3	1st emrg. of new adults
Adıyaman	Kâhta	22-May	2008	300.4	1st emrg. of new adults
Diyarbakır	Ergani	2-Jun	2008	342.6	1st emrg. of new adults
Adıyaman	Merkez	10-Jun	2009	362.8	1st emrg. of new adults
Adıyaman	Kâhta	4-Jun	2009	335.8	1st emrg. of new adults
Diyarbakır	Ergani	12-Jun	2009	405.4	1st emrg. of new adults
Şanlıurfa	Bozova	2-Jun	2010	380.7	1st emrg. of new adults
Şanlıurfa	Hilvan	2-Jun	2010	359.5	1st emrg. of new adults
Şanlıurfa	Siverek	9-Jun	2010	343.6	1st emrg. of new adults

1st adult summary

Cross-check using degreedays.net Tlow=12C
LTAJ Gaziantep, Turkey 37 N. Latitude

Average Date	Degree-days: Sta LTAJ 2018	2019	2020	Avg
2-Jun	505	404	412	440

Range 1st adults

	Earliest	Last
Date:	05/21/08	06/12/09
DDC:	270	405

Average cumulative DDCs across sites

Avg. cumDDCs Tlow=12.89	Conversion factor (see Appendix 1)	Adjusted DDC for Tlow=12.22	Event
44.6	2.3	102	1st egg-laying
342.5	1.4	480	1st emrg. of new adults

← Basis for using 100 DDC for first arrival and completion of OW pre-OV adults
(see Appendix 1 for conversion factors Tlow=12.89 and simple avg calc method used here to preferred Tlow of 12.2C and single sine method)

Results: This is best available estimate of first spring egg-laying at ca. 100 DDC.

Source 3. Kafil, M., A.R. Bandani, M. Kaltenpoth, S.H. Goldansaz, and S.M. Alavi. 2013. Role of symbiotic bacteria in the growth and development of the Sunn pest, *Eurygaster integriceps*. Journal of Insect Science 13:1-12.

- Adults collected from wheat and barley fields in Karaj, Iran, 35:43 Deg. N.
- The study was conducted to measure the impacts of symbiotic microbiota on sunn pest fitness
- They measured development of a control group and other groups given antibiotics at 25 ± 5C and 60 ± 10% RH
- Experiment 1 studied the effect of different concentrations of an antibiotic on growth, development, and adult weight
- Experiment 2 studied the effect of egg surface sterlization on nymphal growth and adult weight
- Below duration data (average days) for the control group is reported (from Tables 2 and 3)
- Analysis for model using Source 3's data: the duration (DDC) of each stage was calculated using a 12.22C threshold

	Days development		Durations in DDC		
	Experiment 1	Experiment 2	Experiment 1	Experiment 2	Average
Egg	5.4	5.5	69.5	70.3	69.9
1st instar	3.1	3.9	39.6	49.8	44.7
2nd instar	3.8	5.5	48.2	69.8	59.0
3rd instar	4.6	5.1	58.8	64.7	61.7
4th instar	5.3	6.0	67.1	77.1	72.1
5th instar	8.1	8.9	103.5	113.9	108.7
Egg to adults	30.3	34.4	386.7	439.6	413.2
Nymphs	24.82	29.36	317.2	375.2	346.2

Results: The coarse resolution of temperature maintenance (25 +/- 5C) and outlier-grade results of this study render it suspect. These results will not be included in the synthesis table.

Source 4. Şimşek, Z. and Yılmaz, T. 1992. Su ve besinin değişik kombinasyonları kullanılarak doğal koşullarda ve iklim odalarında yetiştirilen Süne (*Eurygaster integriceps* Put., Heteroptera: Scutelleridae) nimflerinin canlı kalma oranları ile sürelerinin belirlenmesi. Türkiye II. Entomolooji Kongresi, 28-31 Ocak 1992, Adana. [in Turkish]

- Found that the 2nd instar was the longest and 1st instar was the shortest in duration
- This result contradicts data presented by Source 3 (Kafil et al. 2013) and Source 10 (Abdul-Bassit et al. 2007), who found that the 5th instar was the longest stage

Data from Table 1 show the developmental duration (in days) of different nymph instars in natural conditions, and at 25 and 30C in the laboratory (RH = 65%)

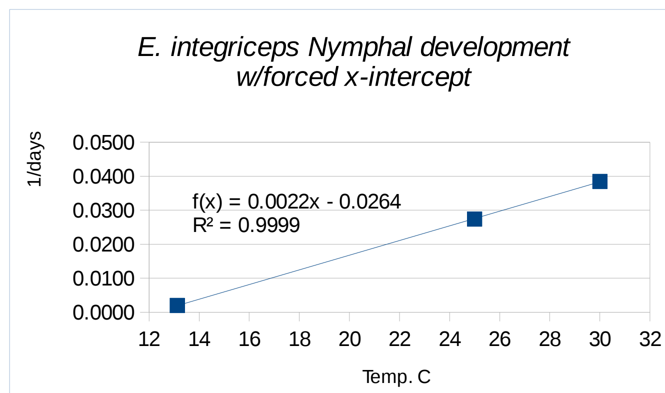
	Outdoors: 14.5-25.5C		Lab: 25C		Lab: 30C	
Stage	Avg.	Range	Avg.	Range	Avg.	Range
1st instar	4.3	(2-8)	5.0	(3-6)	3.2	(2-4)
2nd instar	9.9	(7-15)	9.4	(8-11)	8.3	(6-10)
3rd instar	8.7	(6-20)	7.0	(3-9)	4.4	(4-5)
4th instar	8.1	(5-10)	6.6	(5-11)	4.3	(4-5)
5th instar	8.2	(3-11)	8.5	(7-9)	5.9	(5-7)
Total	39.2		36.5		26.0	

Analysis based on the lab-collected data: calculated durations in DDC using a 12.2C threshold

Stage	25C	30C
1st instar	63.9	56.2
2nd instar	120.3	148.1
3rd instar	89.5	78.9
4th instar	84.3	75.6
5th instar	108.6	104.0
Total	466.6	462.8

Temp C	1/days	days
13.13	0.0020	499
25	0.0274	36.5
30	0.0385	26

slope:	0.0022
intercept:	-0.0264
R-sq:	0.9999
1/slope	464
-b/a	12.22



D. Duçevski. 1969.
Jitnite diervenite v Bulgaria i borbata Steah, 144 p. [in Russian]
- This study was cited within Şimşek & Yılmaz (1992)
- The results are reported below; the original book/article was not obtained (it's unclear if it's a book or an article)
- Analysis for this model based Source 5's data: calculated durations in DDC using a 12.2C threshold

Stage	Duration (days) at 26C (rng = 25.5-26.6)	DDC
1st instar	-	-
2nd instar	8.7	120.1
3rd instar	5.5	75.9
4th instar	6.4	88.3
5th instar	9.1	125.6

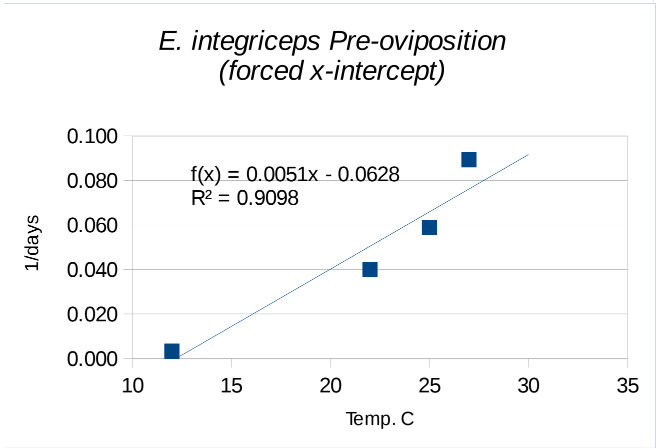
Results: These results do not differ significantly from other studies; This study will not be used in the synthesis as only 1 temperature was used.

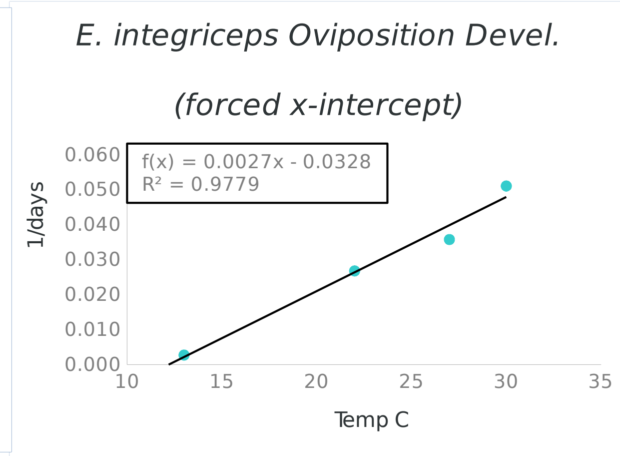
Source 6. Iranipour, S., A.K. Pakdel, and G. Radjabi. 2010. Life history parameters of the Sunn pest, *Eurygaster integriceps*, held at four constant temperatures. Journal of Insect Science 10:1-9.
- Constructed life tables at four constant temperatures: 22, 25, 27, and 30C using Mahdavi wheat kernels as food
- They estimated the duration of pre-OV, OV, post-OV, and the entire adult female stage (longevity)
- Collected adults during diapause termination in December to use in experiments
- Estimated a generation time of 121 days at 22C, and 40 days at 30C
- They concluded that the best reproduction occurred at temps ≥ 25C and that at 30C, and that the upper threshold for reproduction was not yet reached
- Their very high lower threshold of 20C for pre-reproductive development (pre-OV) is clearly incorrect and doesn't make sense
- The most likely possibility is that they calculated the threshold using pre-oviposition data (see below), as these have abnormally different rates than other stages
- This error was pointed out by Kivan 2008 (Source 1), and indicates that pre-OV data are unreliable
- Similarly, generation time had a much higher threshold, so these data were not used either
- Pre-ovipostion DDC was calcuated by forcing the x-intercept through 12.2C, and by deleting 1 point which did not fit the curve at 30C
- If Pre-OV is calculated by subtracting OV period and Post-OV from longevity, it is likely biased due to laboratory or other artifacts
- Data for pre-OV and generation time were estimated from Fig. 3 and 1, respectively, whereas other estimates were reported in the main body of paper

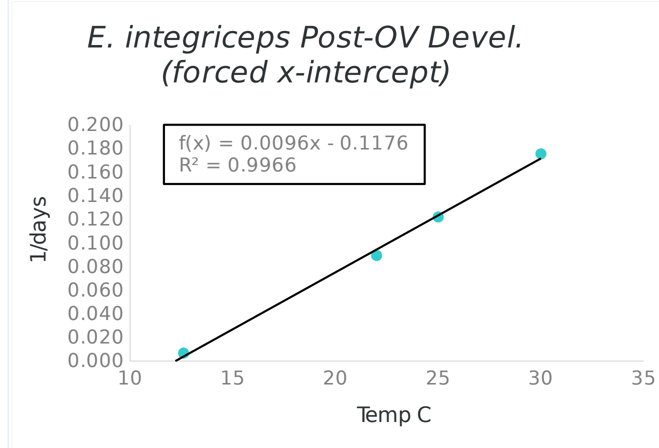
	Days Development				
Temp C	Pre-OV	Oviposition	Post-OV	Longevity	Generation
	300	370	150	250	400
22	25	37.4	11.2	70.8	121
25	17	39.2	8.2	64.9	88
27	11.2	28	3.9	39.2	57
30	6.8	19.6	5.7	30.3	40

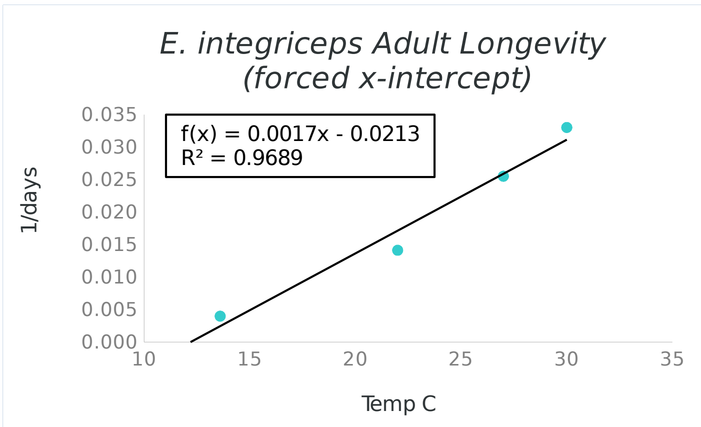
					Dev. Rate (1/days)				
Temp C	Pre-OV	Temp C	Oviposition	Temp C	Post-OV	Temp C	Longevity	Temp C	Generation
11.99	0.003	13	0.003	12.6	0.007	13.6	0.004	13.77	0.0025
22	0.040	22	0.027	22	0.089	22	0.014	22	0.008
25	0.059	25		25	0.122	25		25	0.011
27	0.089	27	0.036	27		27	0.026	27	0.018
30		30	0.051	30	0.175	30	0.033	30	
slope:	0.0051	slope:	0.0027	slope:	0.0096	slope:	0.0017	slope:	0.0010
intercept:	-0.0628	intercept:	-0.0328	intercept:	-0.1176	intercept:	-0.0213	intercept:	-0.0124
R-sq:	0.9098	R-sq:	0.98	R-sq:	1.00	R-sq:	0.97	R-sq:	0.89

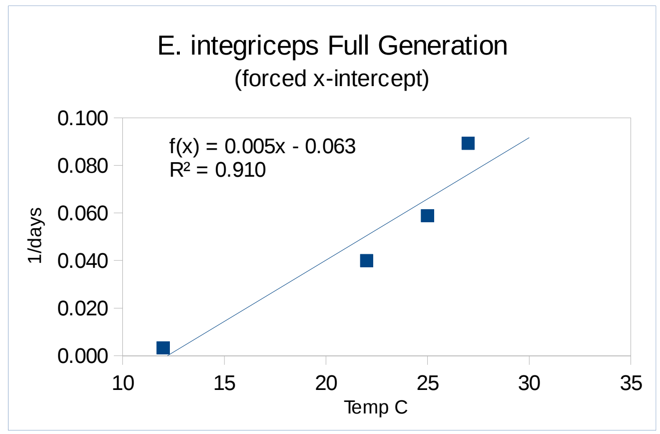
Tlow (F) =	-a/b	53.96	53.95	53.96	53.95	53.95
Tlow(C) =	-a/b	12.20	12.20	12.20	12.20	12.20
DDFs dev =	1/slope	349.6	669.6	186.7	1029.1	1768.8
DDCs dev =	1/slope	194.2	372.0	103.7	571.7	982.6







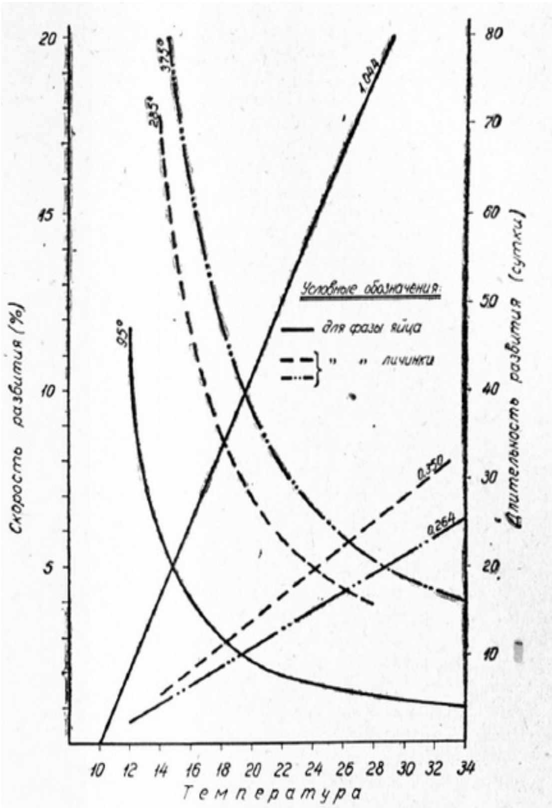




Source 7. Shumakov, N and N. Vingradova. 1958. The ecology of *E. intgriceps*. Trudy Vsesoi͡uznogo instituta zashchity rasteniĭ 9:68-33. [in Russian]
- The translation of the document was not complete - there were issues with OCR text recognition
- In the European USSR the adult bugs leave wintering places in the south occurs in March/April, and in the north in April/May
- However they note the calendar date of departure varies greatly from year to year, only when warm stable weather sets in the temps reach a certain level
- A study in Krasnodar Territory found that emergence occurred at an avg temp above 12C and when max temps reached above 20C
- For example, the first flight in 1951 was on 25-27 March, when max temps were 25.4, 25.7, and 21.2C respectively
- Copulation can be found on crops from the moment of arrival, but most favorable conditions are temps above 24-25C, both during the day and warm nights
- Smolyannikov (1955) indicates the most intensive mating and oviposition occurs at temps of 24-32C
- Gravid females take cover in loose soils. After 7-16 days, after the start of mass flight, the first oviposition occurs
- The oviposition period varies significantly over the years, ranging from 39 to 58-60 days
- At an avg. daily temp of ca. 15C, egg development requires >20 days, while at 20C is takes ca. 10 days
- At an avg. daily temp of 17.9C (avg. max = 25.9C) and no precip, egg development was 7 days, whereas an avg. daily temp of 14.2 (avg. max = 21.6C) it was 19-20 days
- Fig. 6 (below) shows temperature dependent egg development - the data seem very consistent with findings of Kivan (2008) and Gozaucik et al. (2016)
- Across years (1951-1954) the difference in the timing of the beginning of egg hatching was 31 days

- The average duration of mass departure of adults to beginning of egg hatching was 28 days
- At about 25C the first stage larvae progress to the second stage in 3.5-4 days = 48DDC [3.75 * (25 - 12.2C)]
- They documented an average larval duration of 35 days in Krasnodar Krai, and ~28 days in Saratov Region in 1954
- Mass departure of insects for overwintering occurs at avg. daily temps of ca. 24C and maximum of 29-30C

Fig. 6 (pg. 41): The solid black line shows the curve of the dependence of the duration of the development of the egg phase on temp (the sum of the effective temperatures 95) 11 is a straight line characterizing the coefficient of lability of this phase [assuming that the y-axis is the reciprocal of the uncubation period in days]



Source 8. Tafaghodinia, B. and M. Majdabadi. 2006. Temperature based model to forecasting attack time of the Sunn pest *Eurygaster integriceps* Put. in wheat fields of Iran. Proceedings of the 2006 WSEAS Inernational Conference on Mathematical Biology and Ecology, Miami, Florida, USA, Jan 8-20.

- They studied the times and temperatures when adults attacked wheat fields at four different localities in Arak district, Iran in 1992-2001
- The results are presented in Figs 1 and 2, below
- In all years except in 1996 and 1997, the attacks generally began when temps reached ca. 11.5-12.25C

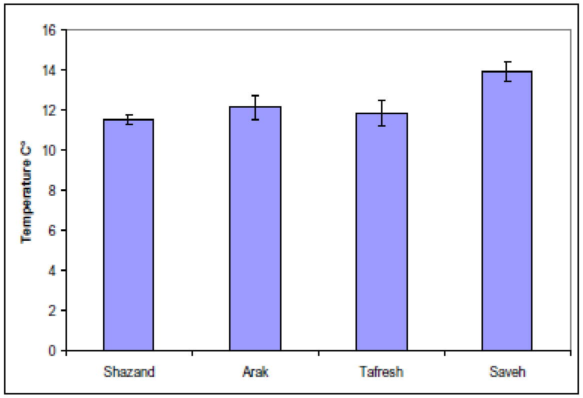


FIG. 1. Temperature of attack time of *E. integriceps* to wheat fields ±SD

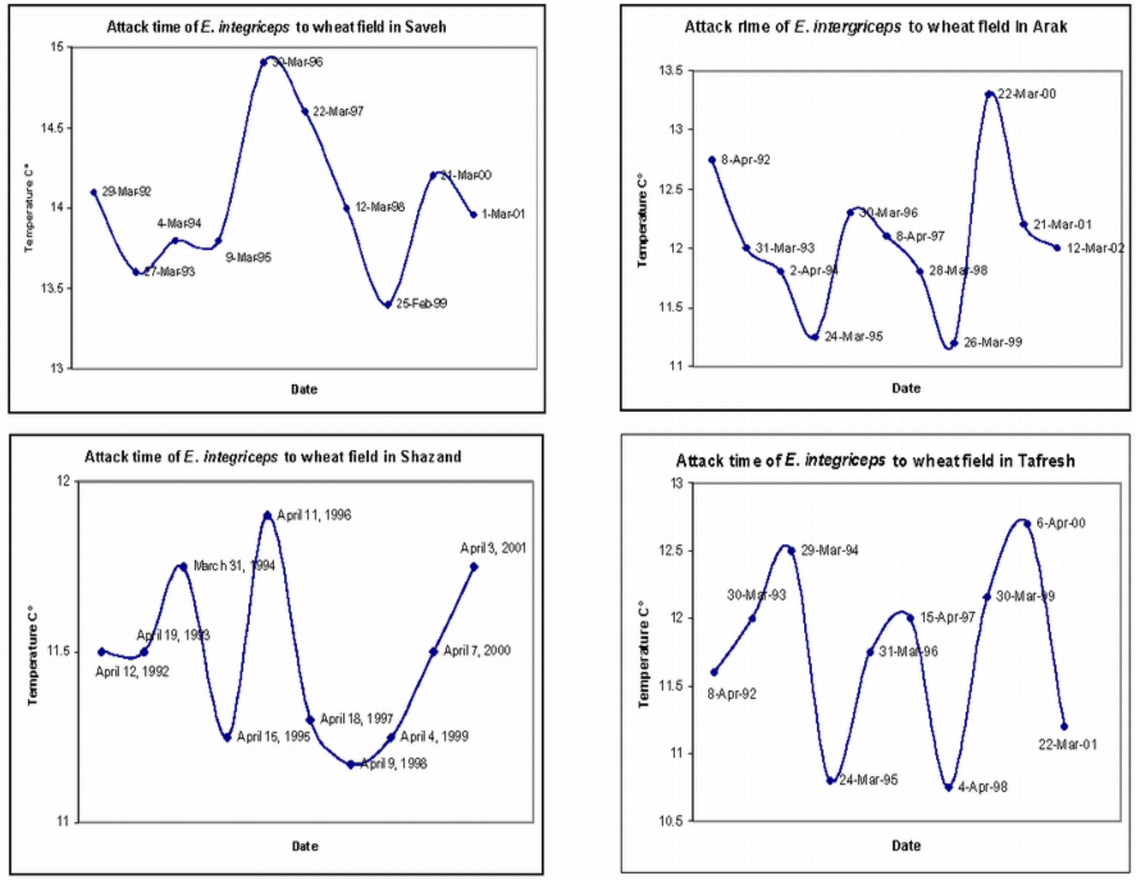


FIG. 2. Attack time of *E. integriceps* to wheat fields by Temperature in four different areas from 992-2001 in Arak district

Source 9. Amir-Maafi, M., M. Majdabadi, F. Aghdasi, B.L. Parker and F. Parsi. 2007. Degree days for forecasting migration of Sunn pest.
***In* Sunn Pest Management: A Decade of Progress 1994-2004, Parker, B.L., M. Skinner, M. Bouhssini, and S.G. Kumari (Eds.). Arab Society for Plant Protection, Beirut, Lebanon.**

- Seasonal flight was monitored from 1992-2002
- They found a base temperature of 0C yielded the lowest CV for DD summations to first migration so they used this in a linear heat unit system
- The number of accumulated DDs to the day of first migration varied between years and locations, likely due to variable temps between air temp and the temp at the OW sites
- Snow cover and radiant heating could be responsible for the variable relationship between air temp and OW site temp
- They conclude that a more accurate predictive index could be developed through an understanding of the relationship between OW site and air temps
- Two studies (Tafaghodinia et al., Source 8 and Martin et al. 1969 [different language]) reported that migration did not occur until temps reached 12-13C, but this study did not find this

Results: In Table 1, Authors reported a C.V. value for our proposed threshold of 12.22 (they used 12.0) to be 44, with a mean DD requirement of 17 using double sine and 35 using low threshold substitution method. From this result, we propose using this threshold of 12.22C and a mean DD total of 40DDC for beginning of migration. Since in Source #8 and as highlighted in source #7, arrival post-migration occurs when temps reach a Tmax of 20C and Tavg of 12C, which tends to occur when simple avg Dds reach ca. 50 DD, . and single sine Dds reach ca. 100 (see Appendix 1).

	Tlow	DD Req.		
First migration	12.22 C	40	DDC	From combined sources #9, #7, others listed above
Migration time	12.22 C	60	DDC	This is based on Source #2, arrival and egg-laying at ca. 100DDC
First Spring Arrival	12.22 C	100	DDC	This is based on Source #2, arrival and egg-laying at ca. 100DDC

Source 10. Abdul-Bassit, MA., H.S. Al-Assadi, and M.A.J. Al-Izzi. 2007. Biological parameters of Sunn pest in wheat and barley fields in northern Iraq. *In* Sunn Pest Management: A Decade of Progress 1994-2004, Parker, B.L., M. Skinner, M. Bouhssini, and S.G. Kumari (Eds.). Arab Society for Plant Protection, Beirut, Lebanon.

- Measured incubation period, nymphal development, and adult life span (no reporting of temperatures) in 20 pairs of adults in outdoor cages
- One pair of adults were placed in each cage for OV and they measured incubation period, nymphal development, and adult life span
- Adults were taken from their hibernation sites at Seffin Mountain (northern Iraq in Erbile district) on March 27, 1999
- The duration of the nymph stage was 27 days on average (range 23-32)
- The duration of each nymph instar (see Table 8) is generally concordant with other studies
- Across 6-8 cages, they measured the duration of the following periods (from Tables 1-3)

Period	Avg. days	Range days
pre-OV	10.2	9-11
OV	33.5	19-38
post-OV	3	1-5
adult male life span	39.6	25-48
adult female life span	46.7	32-53

Compare proportionate times:	This study: Days	Proportion	Iranipour et al. 2010 (#6 above) Dds	Proportion	Days at 27C	Proportion
preov	10.2	23.3	194.2	34.3	11.2	28.6
OV	33.5	76.7	372.0	65.7	28	71.4
total	43.7		566.2		39.2	

Results: The lack of reporting of temperature data makes these results unusable for model parameterization. Assuming temps were similar during adult phases, the proportionate times for the Pre-OV, OV, and post-OV periods could be used to compare to source #6 above: 10.2:33.5 (days pre-OV vs. OV) are at the ratio of 23% to 77%, compared to 34% to 66% for DD reqs in source #6. At the resolution of these data, this is not a meaningful difference.

Source 11. Iranipour, S., A.K. Pakdel, G. Radjabi, and J.P. Michaud. 2011. Life tables for sunn pest, *Eurygaster integriceps* (Heteroptera: Scutelleridae) in northern Iran. Bulletin of Entomological Research 101:33-44.

- Conducted life table studies of sunn pest in Varamin, Iran, from 1998-2011 to determine stage-specifc mortalities and impact of natural enemies on population dynamics
- Reported that oviposition continues for ~1 month so there is considerable overlap in presence of various nymphal stages within a season
- Feeding occurs for 1-2 weeks and then adults migrate to their aestivation (overwintering) sites where they hibernate for 9-10 months
- Found that mortality during the dormancy period was more significant than during premigratory feeding and migrations combined; egg parasitism increased egg mortality
- Food quality and availability is very important to population dynamics
- They did not find strong evidence that climate strongly influenced population variation over the studied years; however, weather conditions were not highly variable across years
- Many other studies have reported that weather conditions were responsible for variation in dynamics across years

Source 12. Makhotin, A.A. 1947. Materials relating to the development of *E. integriceps*. Pages 19-48 *in* Fedotov DM, editor. The Noxious Little Tortoise, *Eurygaster integriceps* Put. Reports on the Work of the Expedition to Central Asia for the Study of the Noxious Little Tortoise organised by the A.N. Severtzov Institute of Evolutionary Morphology. [in Russian]

- The development from egg-laying to molting lasts from 40 up to 50-55 days
- The species may diapuase for several years, e.g., 2 years and 7 months (cited on pg. 22)
- The number of diapausing insects increases starting in September
- Nymphs emerge from eggs in 8-12 days (avg. = 10 days), depending on temperature and weather

- Grivanov (1941) reports that nymphs emerge from eggs in 8-10 days when raised at 22-24C (118 DDC assuming 12.2C threshold) [10 * (24 - 12.20)]
- All post-embyronic development takes 30-40 days depending on temperature
- The reference to "pathologic activity"at temps from 37-48C before they died at 49.5C noted in a review paper was not found, but could have been lost in translation

Source 13. Pekedel'skii, A.A. 1947. Biological foundations of the theory and practice the control of *E. integriceps*. Pages 89-270 *in* Fedotov DM, editor. The Noxious Little Tortoise, *Eurygaster* integriceps Put. Reports on the Work of the Expedition to Central Asia for the Study of the Noxious Little Tortoise organised by the A.N. Severtzov Institute of Evolutionary Morphology.
[in Russian]
- On pg. 197, the author reports that some unsheltered insects exposed to temps of ca. 33-37C appeared to have died from over-heating
- They go on to say that soil surface temps >40C is destructive to the insect (however, note that the soil is hotter than the air temperature)
- Forcibly leaving adults and larvae on soil or asphalt heated to 60-62C resulted in death after an average of 15 and 11 minutes, respectively
- On pg. 203, it appears to state that when soil surfaces reach 55-65C that the insects may not even be able to hide from temps (under lumps of earth)
- In daytime hours when temps reach 34-48C, the insects may move into a shadow or sheltered area (pg. 206)

Source 14. Aljaryian, R., L. Kumar, and S. Taylor. 2016. Modelling the current and potential future distributions of the sunn pest *Eurygaster integriceps* (Hemiptera: Scutelleridae) using CLIMEX. Pest Management Science 72:1989-2000.
- Developed a CLIMEX model for Sunn pest and modeled distribution under future (2030 and 2070) climate conditions
- This source provides the most comprehensive review of developmental requirements and climatic tolerances of sunn pest
- They did not apply a cold stress threshold because it has obligatory winter diapause, stating that the species can survive temps as low as -30C
- They used a heat stress threshold of 45C, as the species can tolerate temps >30C and up to 45C before dying at 49.5C
- The CLIMEX model was modified based on other studies reported in this spreadsheet (see Source 15)

Source 15. Syromyatnikov, M.Y., V.B. Golub, A.V. Kokina, V.A. Soboleva, and V.N. Popov. 2017. DNA barcoding and morphological analysis for rapid identificatoin of most economically important crop-infesting Sunn pests belonging to *Eurygaster* Laporte, 1833 (Hemiptera, Scutelleridae). ZooKeys 706:51-71.
-
-

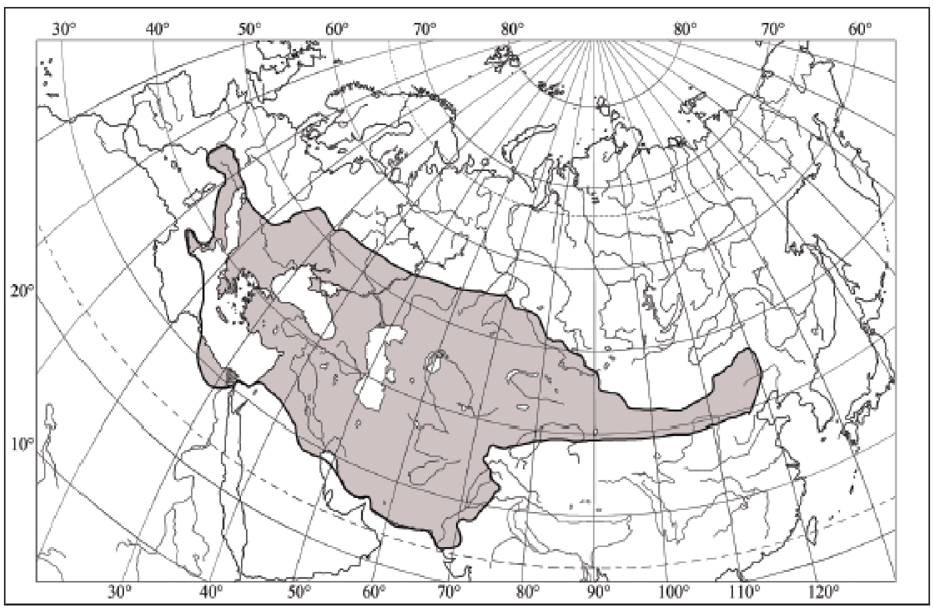
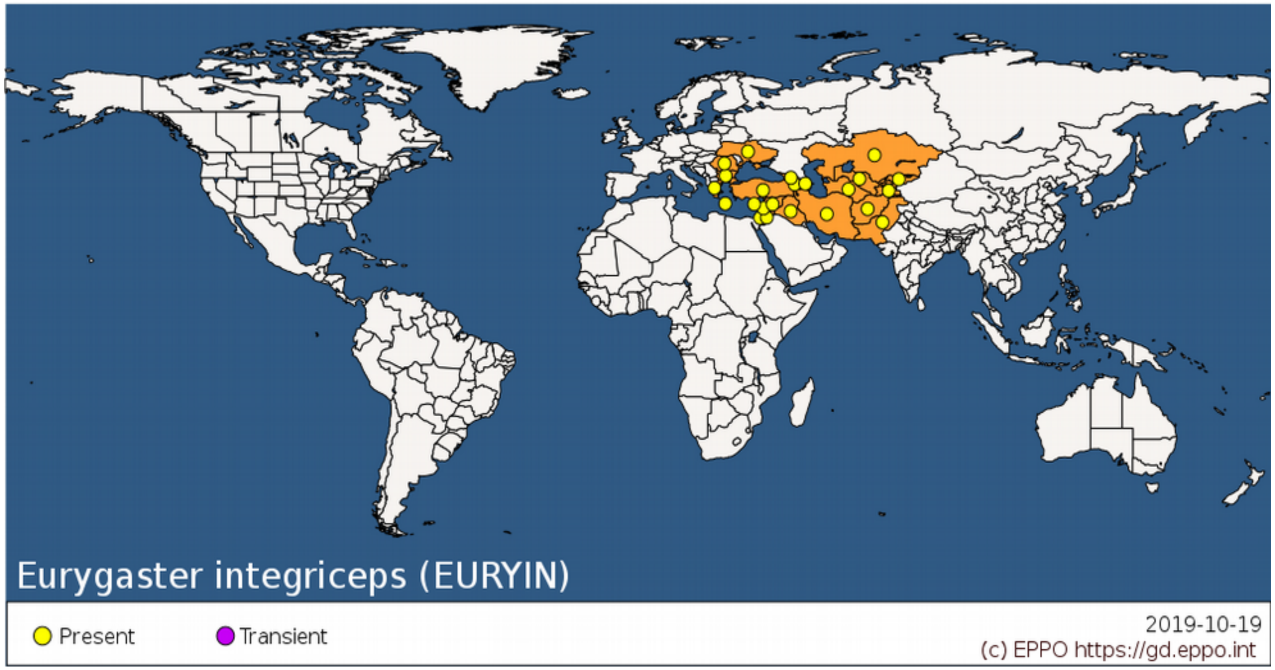


Figure 1. Range of *Eurygaster integriceps* (Puton, 1881) (after Göllner-Scheiding 2006 and Vinokurov et al. 2010).

Source 16. EPPO, 2019. Distribution map for *E. integriceps*
Online at: https://gd.eppo.int/taxon/EURYIN/distribution



The table below summarizes where the species has (or has not) been documented, and whether locality records from this country were available for calibrating a CLIMEX model for sunn pest (see Source 18)

Continent	Country	Code	Locality Records	Source	Notes
Asia	Syria	SY	Yes	Mackesy and Moylett 2018	
	Turkey	TK	Yes	Mackesy and Moylett 2018	
	Lebanon	LB	Yes	Mackesy and Moylett 2018	
	Iran	IR	Yes	Mackesy and Moylett 2018	
	Iraq	IQ	Yes	Mackesy and Moylett 2018	
	Afghanistan	AF	Yes	Mackesy and Moylett 2018	
	Pakistan	PK	Yes	Mackesy and Moylett 2018	
	Kazakhstan	KZ	Yes	Mackesy and Moylett 2018	Problem in West Kazakhstan
	Krygyzstan	KG	Yes	Mackesy and Moylett 2018	
	Tajikistan	TJ	Yes	Mackesy and Moylett 2018	SUNP is rare in central and southern sites (Landis et al. 2016)
	Uzbekistan	UZ	Yes	Mackesy and Moylett 2018	
	Armenia	AM	No	Mackesy and Moylett 2018	
	Azerbaijan	AZ	Yes	Mackesy and Moylett 2018	
	Georgia	GE	No	Mackesy and Moylett 2018	
	Israel	IL	Yes	Mackesy and Moylett 2018	
	Jordan	JO	Yes	Mackesy and Moylett 2018	
Europe	Belarus	BY	Yes	Shumakov and Vingraova 1958	
	Bulgaria	BG	Yes	Mackesy and Moylett 2018	
	Croatia	HR	No	Ozberk et al. 2005	

	Cyprus	CY	Yes	Mackesy and Moylett 2018	
	Greece	GR	Yes	Mackesy and Moylett 2018	
	Italy	IT	No	Salis et al. 2013	Absent in Sardinia; not known to be in Italy?
	Macedonia	MK	No	Mackesy and Moylett 2018	
	Maldova	MD	Yes	Mackesy and Moylett 2018	
	Montenegro	ME	No	Ozberk et al. 2005	
	Romania	RO	Yes	Mackesy and Moylett 2018	
	Russia	RU	Yes	Mackesy and Moylett 2018	
	Serbia	RS	No	Mackesy and Moylett 2018	
	Ukraine	UK	Yes	Mackesy and Moylett 2018	
Africa	Algeria	DZ	No	Mackesy and Moylett 2018	No records at all from Africa - species is not native there
	Morocco	MA	No	Aljaryian et al. 2016	
	Tunisia	TN	No	Aljaryian et al. 2016	

Source 17. Pavlyushin, V.A., N. Vilkova, G.I. Suchoruchenko, and L.I. Nefedova. 2010. Species habitat and zones of harmfulness of the wheat bug (In Russian) Zashchita i Karantin Rastenii. 1:58-62. https://www.cabdirect.org/cabdirect/abstract/20103321468

- The authors review information on the ancestral (native) range of the species, which they report is central Asia in mountain and foothill (<2000 m) territories of Transcaucasia, Iraq, Iran, Afghanistant and Tajikstan
- The species spread as people began planting cereal crops in other regions, becoming particularly problematic began in in the last quarter of the 19th century
- It increased in number and expansion in the Caucasus, Volga region and western Kazakhstan in the 1960-1970s
- Estimate that the modern range is 4-5 times larger in area than its original ancestral area and continues to expand by diffusion

Source 18. CLIMEX model modified from Aljaryian et al. 2016 (this study)

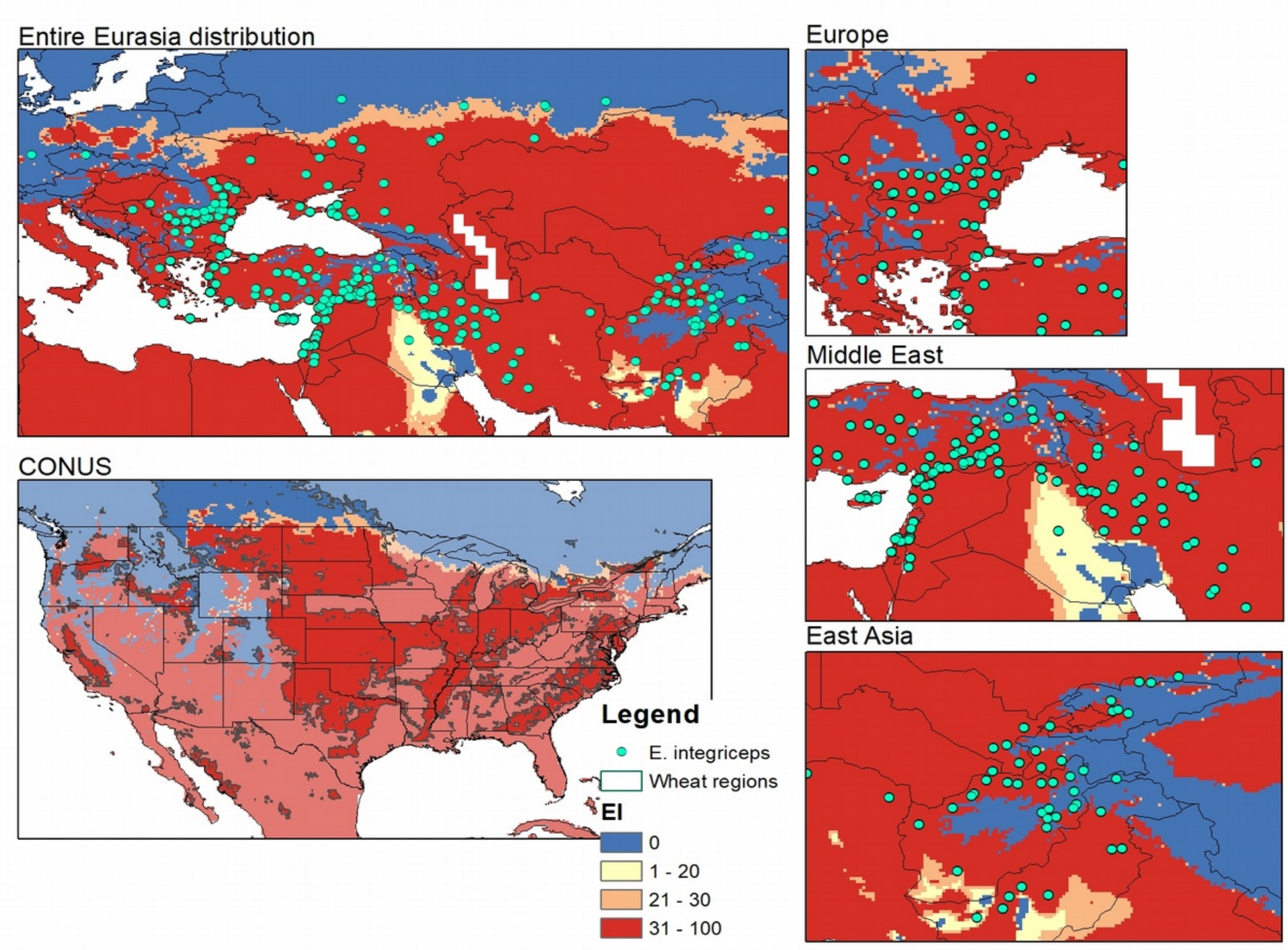
- Uses same parameter values as Aljarian et al. 2016 except:
  1) used a cold stress threshold of -30C (they did not use the CS threshold, and rationale doesn't make much sense)
  2) lowered heat stress threshold to 40C - theirs seemed to high
  3) used a generation degree-day length (PDD) of 784 (100 DDs emergence + egg DD + larvaeDD + pupaeDD) - so pop growth occurs if insect makes it to OW stage that year
     Note: using the gen time estimated above (990 DD) resulted in the exclusion of all northernmost localities (in Russia)
  4) all developmental parameters (DV0, DV1, DV2, and DV3) were changed based on analyses above
  5) used a DV0 of 11C instead of 12C because northernmost points at approx. 55N were being excluded

Table of CLIMEX parameters used for this study. Highlighted cells are parameters that were modified from the model of Aljaryian et al. 2016

Moisture Index						
SM0	SM1	SM2	SM3			
0.01	0.02	1.3	2.5			
Temperature Index						
DV0	DV1	DV2	DV3			
11	18	32	36			
Cold Stress						
TTCS	THCS	DTCS	DHCS	TTCSA	THCSA	
-30	-0.00025	0	0	0	0	
Heat Stress						
TTHS	THHS	DTHS	DHHS			
40	0.003	0	0			
Dry Stress						
SMDS	HDS					
0.01	-0.005					
Wet Stress						
SMWS	HWS					
2.5	0.002					
Degree-days per Generation						
PDD						
784						

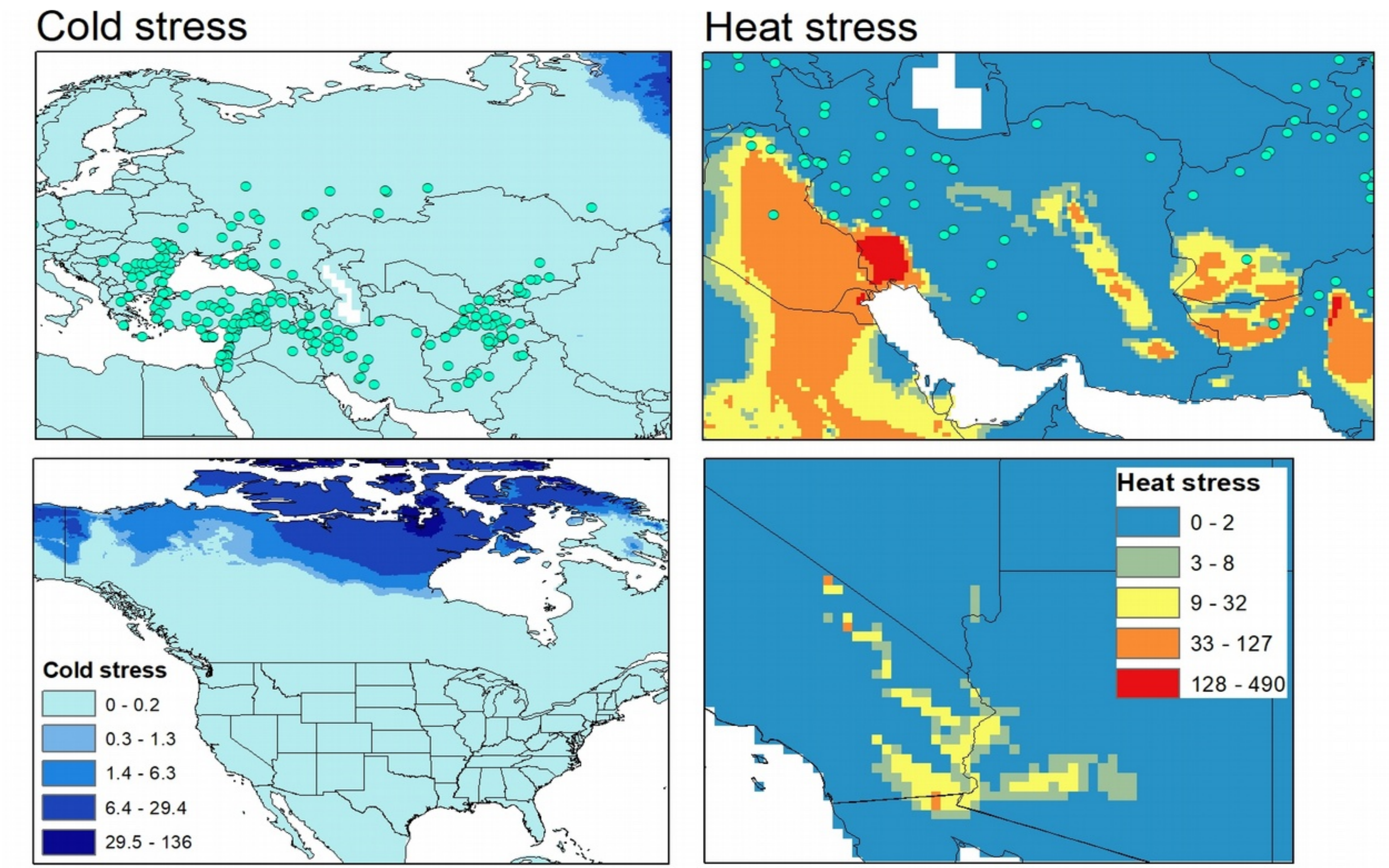
CLIMEX maps of the ecoclimatic index

- Some northernmost localities excluded - perhaps species can complete development faster at range edge (or lower thresholds - further work needed)
- Wheat growing regions in CONUS are indicated - essentially Sunn pest could occur anywhere in CONUS based on these results
- 232 of 257 localities (90%) had EI values greater than 20; 17 localities had EI values between 0 and 20 (the rest had missing data because of CLIMEX data's coarse resolution)



CLIMEX maps of cold and heat stress

- Cold stress does not exclude the species from anywhere in Eurasia and CONUS
- With a couple of exceptions, the species does not occur in areas where heat stress is greater than ca. 32 units (the map below zooms in on the hottest part of its distribution)
- Thus heat stress would likely not exclude the species from anywhere in CONUS except perhaps in a few tiny areas (where heat stress is greater than ca. 32 units)

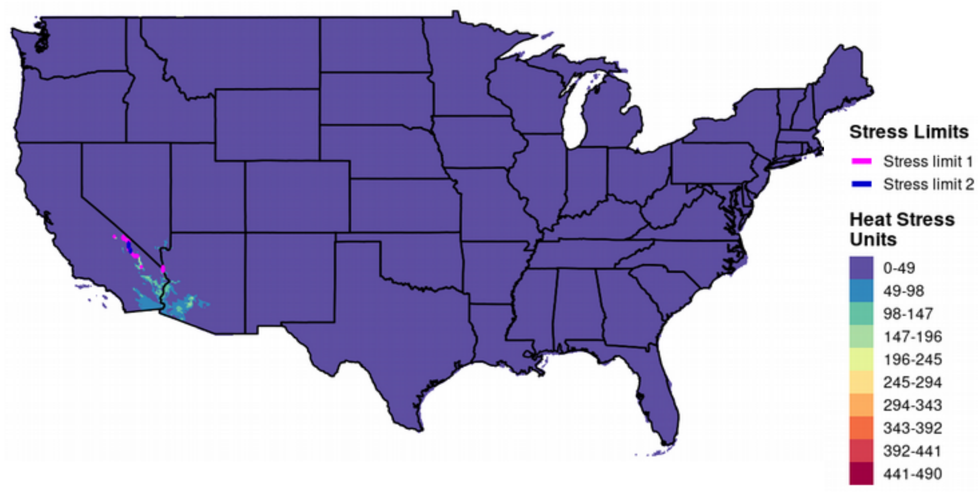


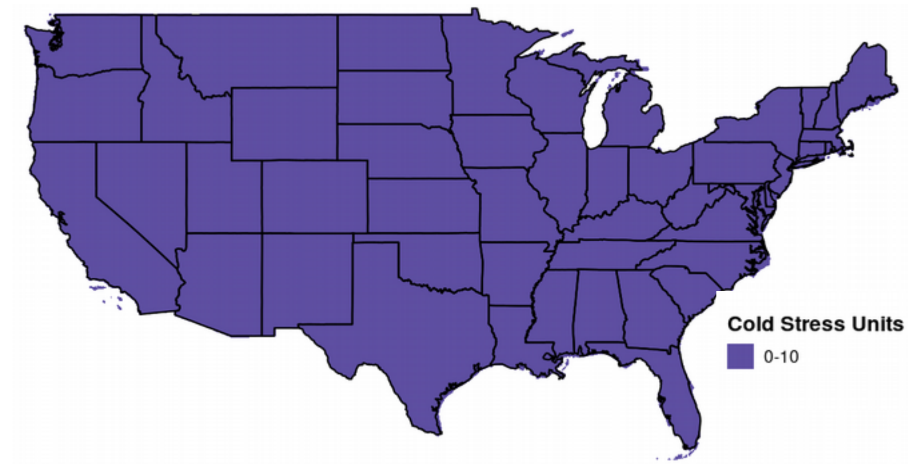
Source 19. DDRP climate suitability model (this study)

- Calibrating cold stress limits isn't possible because according to CLIMEX the species would not be exlcuded anywhere in CONUS
- Heat stress limits result in potential exclusions only in a very small area (Death Valley and vicinity), generally consistent with CLIMEX

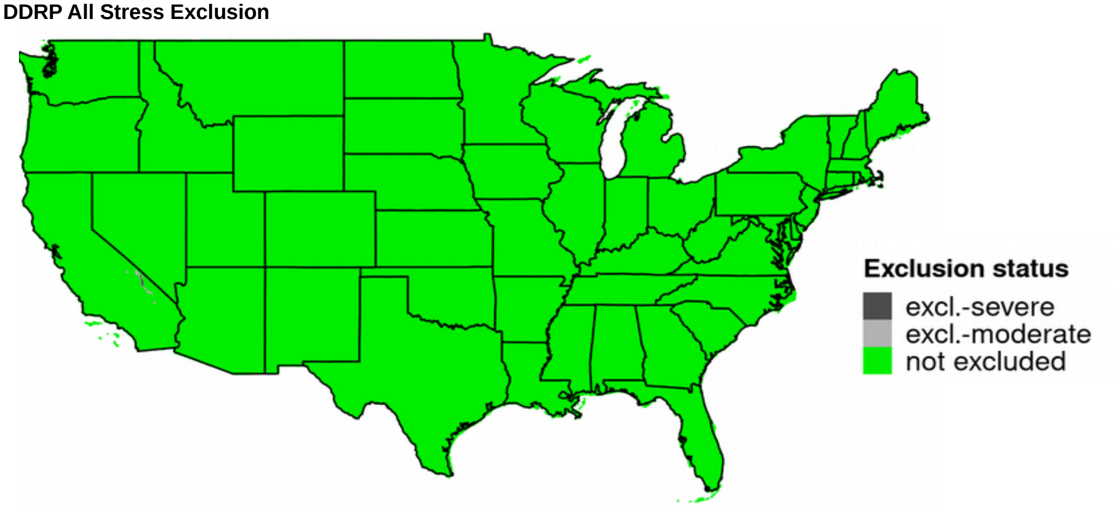
DDRP Cold Stress	Value	Units
cold stress threshold	-30.0	C
limit 1 (mod. cold stress)	10	DDC
limit 2 (sev. cold stress)	25	DDC

DDRP Heat Stress	Value	Units
heat stress threshold	40.0	C
limit 1 (mod. heat stress)	200	DDC
limit 2 (sev. heat stress)	400	DDC





DDRP All Stress Exclusion



Appendix 1 – To support analysis of Source #2 results

Goal: Develop a conversion factor from reported Tlow=12.89 C and Simple Avg calc method to Tlow=12.22 C and Single Sine calc method

Rationale: 1) Significant difference in thresholds justifies conversion; 2) Simple average method tends to underestimate heat units compared to more complex methods in spring and fall seasons, 3) Several reports (#7 & #8) state that adults arrive in wheat fields when daily max temps reach ca. 20C, daily avg temps reach ca. 12C.

Methods: Using DD calculator at USPEST.ORG, sample data from U.S. locations with somewhat similar (temperate continental) climates to Turkey, compare DDC for conditions of their study (Tlow 12.89 and simple average calculations) to our preferred threshold of 12.22 and calculation method of single sine. The average ratio of the DDC values will be used for the conversion. In additon, find DD accumulation (Tlow=12.22, Single Sine) and date when Tmax generally reaches 20C and Tavg generally reaches 12C.

Simple Avg **Tlow=12.89** **DDC = 44.6**	**Event: 1st Egg-laying in Spring** **Average date reported:**	04/22/00	**2018**	**2019**	**2020**
KP28	**(12.89, A)**		45	74	60
Med Lodge, KS	**(12.22, SS)**		145	138	140
	DDs when Tavg=12, Tmax=20		103	98	121
	Date when Tavg=12, Tmax=20		04/10/18	04/15/19	04/16/20
KHSB	**(12.89, A)**		42	54	51
Harrisburg, IL	**(12.22, SS)**		83	107	110
	DDs when Tavg=12, Tmax=20		91	84	105
	Date when Tavg=12, Tmax=20		04/25/18	04/16/19	04/20/20
KLEX	**(12.89, A)**		64	82	56
Lexington, KY	**(12.22, SS)**		114	143	109
	DDs when Tavg=12, Tmax=20		84	68	120
	Date when Tavg=12, Tmax=20		04/12/18	04/06/19	04/28/20
KDUX	**(12.89, A)**		53	60	49
Dumas, TX	**(12.22, SS)**		175	161	150
	DDs when Tavg=12, Tmax=20		86	78	54
	Date when Tavg=12, Tmax=20		03/22/18	04/01/19	03/22/20
KAVK	**(12.89, A)**		63	85	73
Alva, OK	**(12.22, SS)**		164	150	153
	DDs when Tavg=12, Tmax=20		114	108	90
	Date when Tavg=12, Tmax=20		04/10/18	04/15/19	04/05/20
Averages	**(12.89, A)**		60.7		
	(12.22, SS)		136.1		
	DDs when Tavg=12, Tmax=20		93.6		
	Date when Tavg=12, Tmax=20		04/11/19		
Ratio (12.22 SS divided by 12.89 A):			3.2	1.9	2.3
			2.0	2.0	2.2
			1.8	1.7	1.9
			3.3	2.7	3.1
			2.6	1.8	2.1
Overall average Ratio:			2.3	0.5	23.6

Results: For the 5 sites x 3 years, the average DD accumulation on April 22 was 61 using a 12.89 Tlow and simple average method, versus 136 DD using a 12.22 Tlow and single sine method, for an overall average ratio of 2.3. The average DD accumulation and date when Tmax tended to reach 20C and Tavg tended to reach 12C were 94 DD and April 11. This result tends to support reports made in sources #7 and #8 concerning arrival of adults in wheat fields in Russia and Iran.

Verification/partial validation (using 3 stations, 3 years):

Event: 1st Egg-laying in Spring

		DDCs on 4/22/00		
		2018	**2019**	**2020**
KCDS	**(12.89, A)**	169	146	139
Childress TX	**(12.22, SS)**	321	253	258
KSYI	**(12.89, A)**	97	93	108
Shelbyville TN	**(12.22, SS)**	166	173	188
KTCC	**(12.89, A)**	93	89	91
Tucumcari NM	**(12.22, SS)**	268	242	228
Averages	**Average DDC (12.89; simple avg)**	**114**		
	Average DDC (12.22; single sine)	**233**		
	Ratio (of averages):	**2.0**		
	ratio	**1.9**	**1.7**	**1.9**
		1.7	**1.9**	**1.7**
		2.9	**2.7**	**2.5**
	avg ratio 2.1			

Results: for the 3 sites x 3 years, for the date April 22, the average DDs were 114 and 233 (Tlow=12.89/Avg vs. Tlow=12.22/Single sine), and average ratio was 2.1, close to value of 2.3 obtained for 5 other sites.