Phenology/Degree-Day and Climate Suitability Model Analysis – July 1, 2009, updates June 2016, July 2020

by Len Coop and Brittany Barker, Oregon IPM Center, Oregon State University for APHIS PPQ

Silver Y Moth ***Autographa gamma*** **L. (Lepidoptera: Noctuidae)**

Hosts: highly polyphagous (vegetables including garden pea, sugar beet, cabbage, cauliflower) Native to: Nearctic Region

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

Adult moth (photo by Julieta Brambila)

Caterpillar (photo by Tapio Kujala)

Pupa

Thresholds, degree-days, events and climate suitability params used in Silver Y Moth model:

Parameter abbr.	Description	degF	degC	DDF	DDC
eggLDT	egg lower dev threshold	48.0	8.89	-	-
eggUDT	egg upper dev threshold	95.0	35.0	-	-
larvaeLDT	larvae lower dev threshold	48.0	8.89	-	-
larvaeUDT	larvae upper dev threshold	95.0	35.0	-	-
pupaeLDT	pupae lower dev threshold	48.0	8.89	-	-
pupaeUDT	pupae upper dev threshold	95.0	35.0	-	-
adultLDT	adult lower develpmental threshold	48.0	8.89	-	-
adultUDT	adult upper dev threshold	95.0	35.0	-	-
eggDD	duration of egg stage in DDs	-	-	96	53
larvaeDD	duration of larva stage in DDs	-	-	437	243
pupDD	duration of pupa stage in DDs	-	-	235	131
adultDD	duration of pre-OV plus time to 50% OV in DDs	-	-	232	129
OWlarvaeDD	DDs until OW larvae first pupation	-	-	65	36
eggEventDD	DDs into egg stage when hatching begins	-	-	96	53
larvaeEventDD	DDs until mid-larval deveopment	-	-	220	122
pupaeEventDD	DDs until mid-pupal development	-	-	118	65
adultEventDD	DDs until first catch in traps	-	-	59	33
coldstress_threshold	cold stress threshold	30.2	-1	-	-
coldstress_units_max1	cold stress degree day limit when most individuals die	-	-	675	375
coldstress_units_max2	cold stress degree day limit when all individuals die	-	-	6480	3600
heatstress_threshold	heat stress threshold	100.4	38.0	-	-
heatstress_units_max1	heat stress degree day limit when most individuals die	-	-	468	260
heatstress_units_max2	heat stress degree day limit when all individuals die	-	-	1080	600

distro_mean	average DDs to OW larvae first pupation	160
distro_var	variation in DDs to OW larvae first pupation	5000
xdist1	minimum DDs (°C) to OW larvae first pupation	36
xidst2	maximum DDs (°C) to OW larvae first pupation	231
distro_shape	shape of the distribution	normal

PHENOLOGY MODEL

Note values highlighted with yellow were added for forcing x-intercept or removed as non-linear

1. Source: Honěk, A., V. Jarošík, Z. Martinková, and I. Novák. 2002. Food induced variation of thermal constants of development and growth of *Autographa gamma* (Lepidoptera: Noctuidae) larvae. European Journal of Entomology. 99:241-252

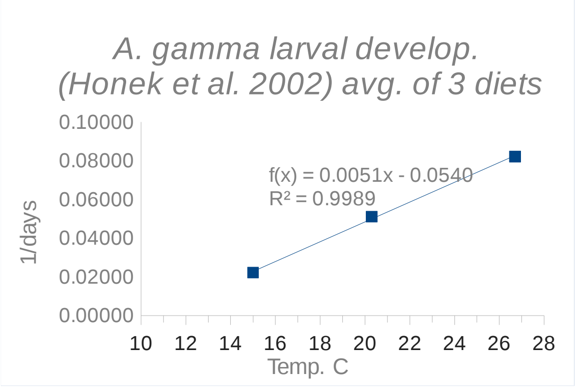
- populations collected as adults flying in alfalfa fields in Prague, Czech Republic.
- reared larvae at three temperatures on numerous hosts, recording mortality and development time.
- solved for lower developmental thresholds ranging from 9.3 to 11.0C on the 11 hosts where larvae completed development.

Larval Development

			Host (better than average diets)			
			T. officinale	A. retroflexus	P sativa	Avg
Temp	1/days	Days				
15	0.02219		36.4	56.9	41.9	45.1
20.3	0.05111		17.4	24.4	16.9	19.6
26.7	0.08219		10.3	14.5	11.7	12.2

Regression (use average of three diets; no forcing)

1/slope	195.3	slope	0.0051
x intercept	10.5	intercept	-0.0540
		R-sq	0.9989

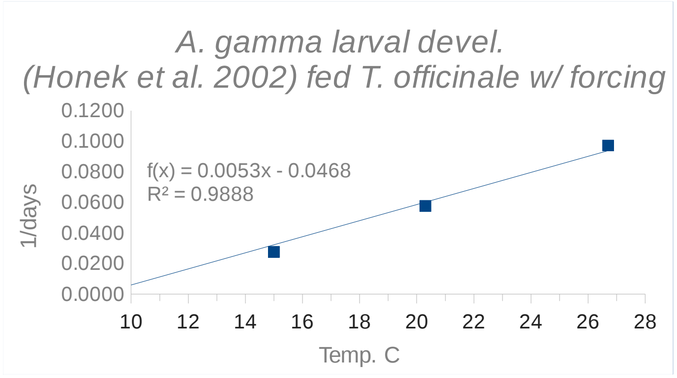


Regression each diet separately (w/forcing)

***Taraxacum officinale* (common dandelion)**

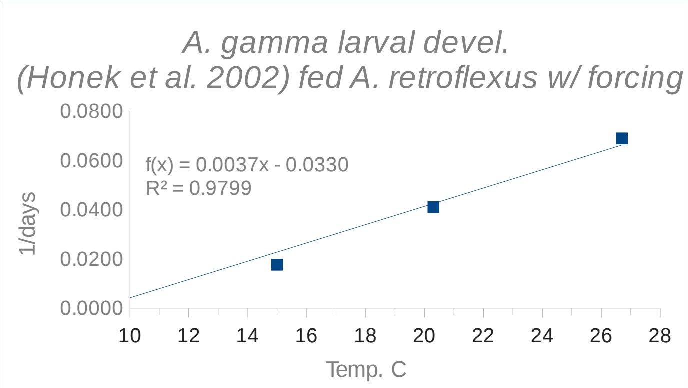
Temp	1/days	Days
8.612	0.0025	400.0
15	0.0275	36.4
20.3	0.0575	17.4
26.7	0.0971	10.3

1/slope	190	slope	0.0053
x intercept	8.889	intercept	-0.0468
		R-sq	0.9888



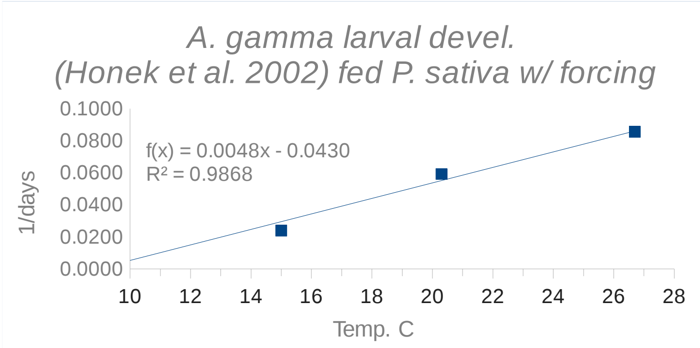
Amaranthus retroflexus **(redroot pigweed)**

			Temp	1/days	Days
			8.535	0.0025	400.0
			15	0.0176	56.9
			20.3	0.0410	24.4
			26.7	0.0690	14.5
1/slope	269	slope		0.0037	
x intercept	8.889	intercept		-0.0330	
		R-sq		0.9799	



Pastinaca sativa **(parsnip)**

			Temp	1/days	Days
			8.9315	0.0025	400.0
			15	0.0239	41.9
			20.3	0.0592	16.9
			26.7	0.0855	11.7
1/slope	207	slope		0.0048	
x intercept	8.889	intercept		-0.0430	
		R-sq		0.9868	



Avg. 1/slope: 222

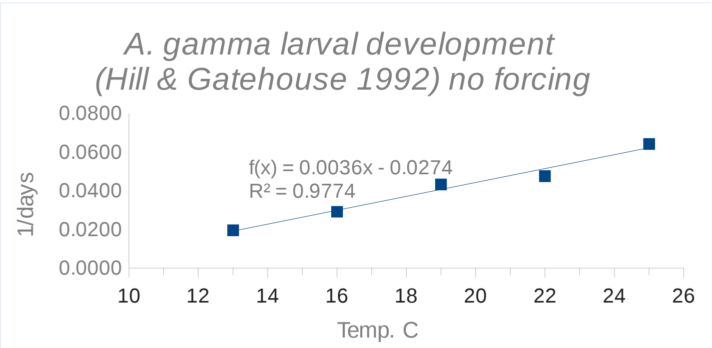
Results: For larvae reared on 3 plant diets, with no forcing x-intercept was 10.3C. Larval development using a forced x-intercept of 8.889C ranged from 190 to 269 DD, average 222 DD.

2. Hill, J.K. and A.G. Gatehouse. 1992. Effects of temperature and photoperiod on development and pre-reproductive period of the silver Y moth *Autographa gamma* (Lepidoptera: Noctuidae). Bull. Entomol. Res. 82:335-341.

From Table 1. (Females only)

Larvae – no forcing

Temp C		1/days	Larval days
	13	0.0195	51.2
	16	0.0291	34.4
	19	0.0431	23.2
	22	0.0474	21.1
	25	0.0641	15.6
slope		0.0036	
Y-intercept		-0.0274	
R-sq		0.9774	(7.2=0.987)
X-intercept (-b/a)		7.655	
Dds (1/slope)		279.16	



Larval Development

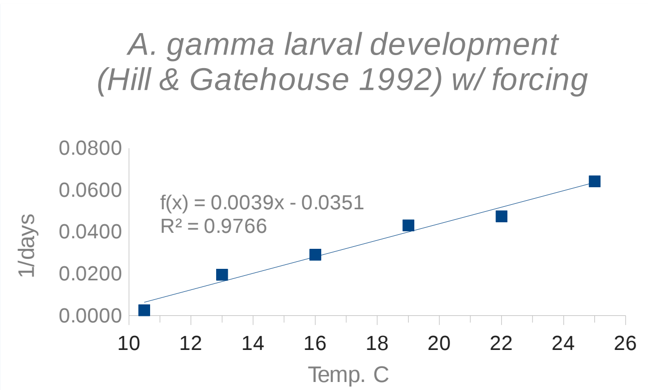
Temp C	1/days	Larval days
10.493	0.0025	400
13	0.0195	51.2
16	0.0291	34.4
19	0.0431	23.2
22	0.0474	21.1
25	0.0641	15.6
slope	0.0039	
Y-intercept	-0.0351	
R-sq	0.9766	
X-intercept (-a/b)	8.889	
Dds (1/slope)	253.56	

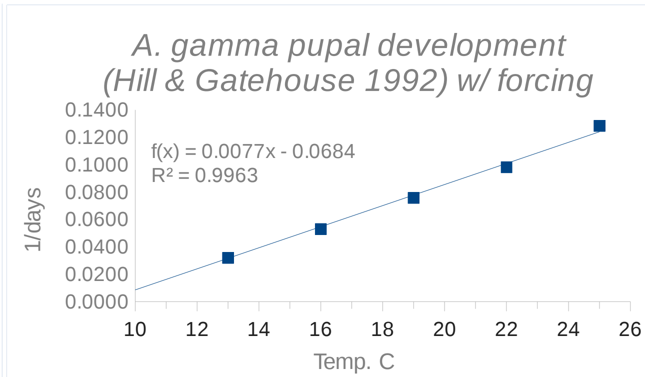
Pupal Development

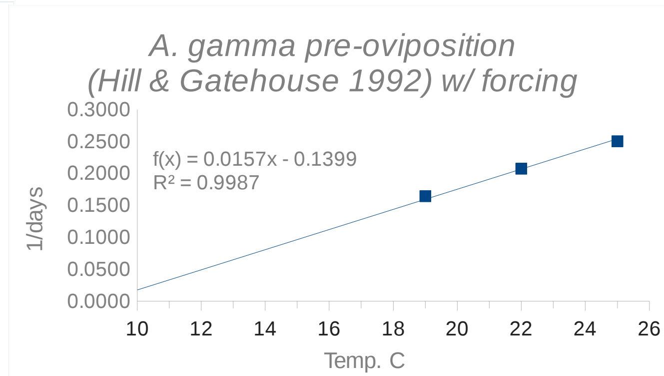
Temp C	1/days	Pupal days
9.053	0.0033	300
13	0.0319	31.3
16	0.0529	18.9
19	0.0758	13.2
22	0.0980	10.2
25	0.1282	7.8
slope	0.0077	
Y-intercept	-0.0684	
R-sq	0.9963	
X-intercept	8.889	
Dds (1/slope	129.99	

Pre-oviposition time

Temp C	1/days	PreOV days
9.337	0.0050	200
13		6.67
16		6.49
19	0.1642	6.09
22	0.2070	4.83
25	0.2500	4
slope	0.0157	
Y-intercept	-0.1399	
R-sq	0.9987	
X-intercept	8.889	
Dds (1/slope	63.52	

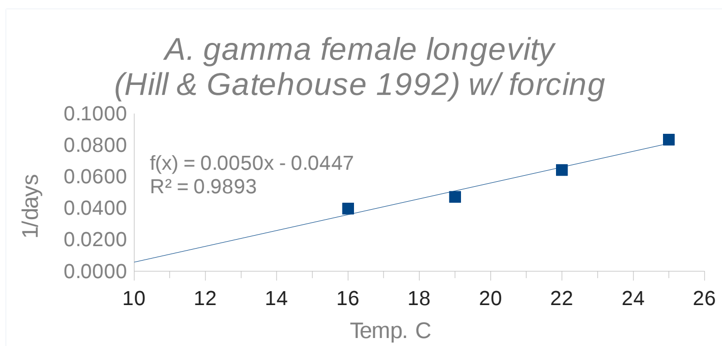






Female Longevity (from Table 2)

Temp C	1/days	Longev. Days
9.615	0.0033	300
13		32.3
16	0.0395	25.3
19	0.0469	21.3
22	0.0641	15.6
25	0.0833	12
slope	0.0050	
Y-intercept	-0.0447	
R-sq	0.9893	
X-intercept	8.889	
Dds (1/slope)	198.83	



Results: Larval stage lower threshold (no forcing) was 7.66C. Forcing through an x-intercept of 8.889C, DD requirements were 254, 130, and 64 DD for larval, pupal and pre-OV stages.

3. Harakly, F. A. 1975. Biological studies on the loopers *Autographa gamma* (L.) and *Cornutiplusia circumflexa* (L.) (Lep., Noctuidae) infesting truck crops in Egypt. Z. Ang. Ent. 78:285-290.

Egg Development

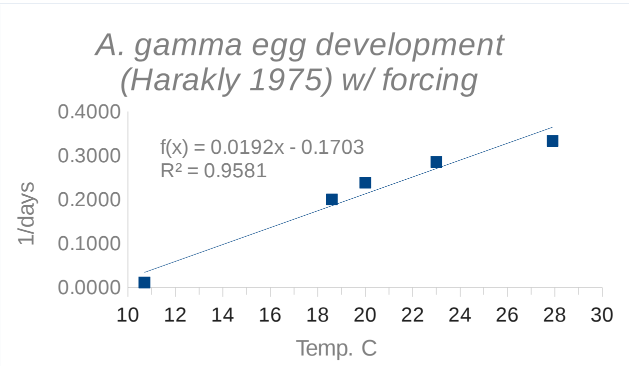
	Temp. C	1/days	days eggs
	10.6923	0.0111	90
	18.6	0.2000	5
	20	0.2381	4.2
	23	0.2857	3.5
	27.9	0.3333	3
slope		0.0192	
Y-intercept		-0.1703	
R-sq		0.9581	
X-intercept (-a/b)		8.8892	
Dds (1/slope)		52.2	

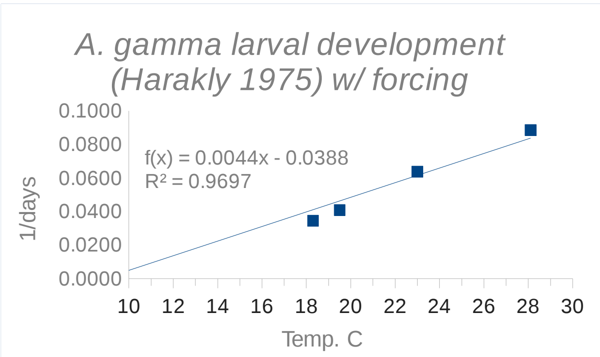
Larval Development

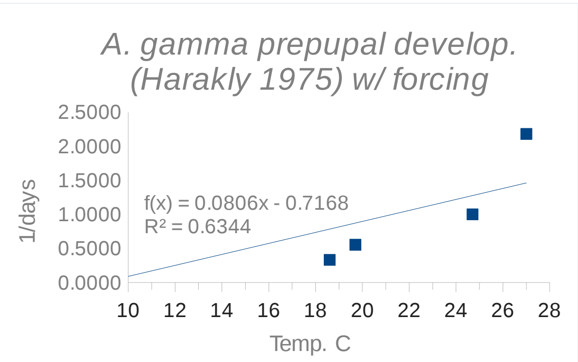
	Temp. C	1/days	days larvae
	8.383	0.0029	350
	18.3	0.0345	29
	19.5	0.0408	24.5
	23	0.0637	15.7
	28.1	0.0885	11.3
slope		0.0044	
Y-intercept		-0.0388	
R-sq		0.9697	
X-int. (-a/b)		8.8890	
Dds (1/slope)		229.4	

Prepupal Development

	Temp. C	1/days	days prepupae
	5.963	0.0833	12
	18.6	0.3333	3
	19.7	0.5556	1.8
	24.7	1.0000	1
	27	2.1818	0.46
slope		0.0806	
Y-intercept		-0.7168	
R-sq		0.6344	
X-int. (-a/b)		8.8896	
Dds (1/slope)		12.4	







Larval+Prepupal Development

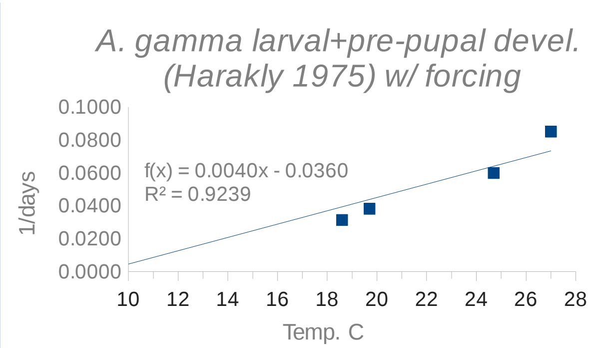
	Temp. C	1/days	days larvae plus prepupae
	8	0.0027	372.3
	18.6	0.0313	32
	19.7	0.0380	26.3
	24.7	0.0599	16.7
	27	0.0850	11.8
slope		0.0040	
Y-intercept		-0.0360	
R-sq		0.9239	
X-intercept (-a/b)		8.8890	
Dds (1/slope)		246.9	

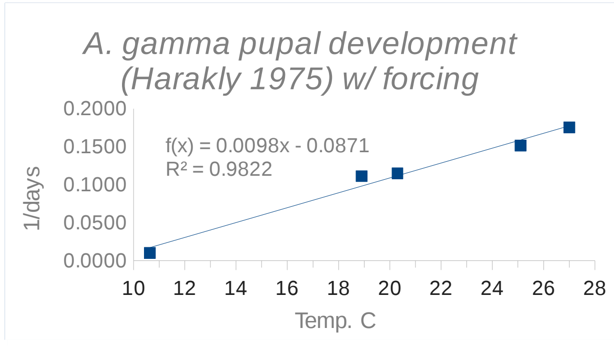
Pupal Development

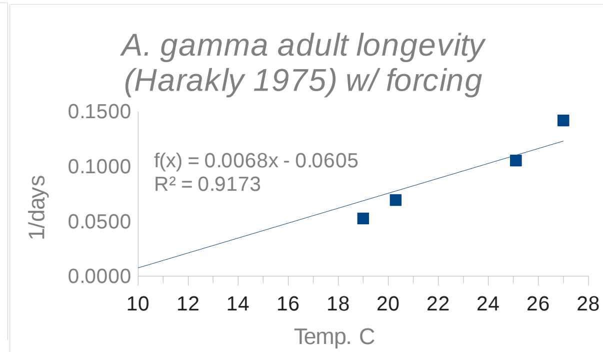
	Temp. C	1/days	days pupae
	10.6344	0.0102	98
	18.9	0.1111	9
	20.3	0.1149	8.7
	25.1	0.1515	6.6
	27	0.1754	5.7
slope		0.0098	
Y-intercept		-0.0871	
R-sq		0.9822	
X-int. (-a/b)		8.8891	
Dds (1/slope)		102.1	

Adult longevity

	Temp. C	1/days	days adult longevity	Life history Egg-to-death
	9	0.0116	86.53	
	19	0.0526	19	65
	20.3	0.0694	14.4	53.6
	25.1	0.1053	9.5	36.3
	27	0.1420	7.0	27.5
slope		0.0068		
Y-intercept		-0.0605		
R-sq		0.9173		
X-int. (-a/b)		8.8891		
Dds (1/slope)		146.9		







Results: With forcing of x-intercept through 8.889C, DD requirements were 52, 229, 12, 247, 102, and 146 DD for eggs, larvae, pre-pupae, larvae+pre-pupae, pupae, and adult longevity.

4. Taha, M.A., H.A. Abd-El Wahab, H.I. Mahmoud and G. El S. Abd et Hamed. 2012. Effect of different temperature, thermal threshold units on development of silvery Y moth, *Autographa gamma*. Linn. J. Plant Prot. And Path., Mansoura Univ. 3:355-361

- Research conducted in Egypt (assume Cairo and Giza), larvae collected from artichoke fields, reared in constant temperature incubators. Larvae fed artichoke leaves.
- Used x-intercept method to solve for lower thresholds of 7.5, 10.8, 3.0, 8.8, and 9.4C for egg, larval, pupal, egg-to-adult, and full generation development, respectively.
- Also solved for lower thresholds of 10.3 and 9.1C for female longevity and full life span, respectively.

Egg Development

Temp. C	1/days	days eggs
9.6467	0.0111	90
20	0.2222	4.5
25	0.2857	3.5
30	0.4000	2.5

slope	0.0187
Y-intercept	-0.1664
R-sq	0.9939
X-intercept (-a/b)	8.8890
Dds (1/slope)	53.4

Larval Development

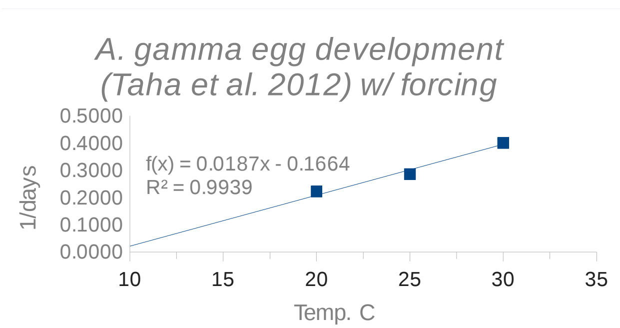
Temp. C	1/days	days larvae
9.0055	0.0025	400
20	0.0396	25.26
25	0.0522	19.14
30	0.0828	12.08

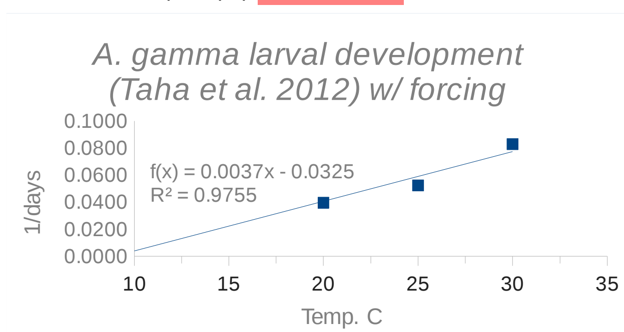
slope	0.0037
Y-intercept	-0.0325
R-sq	0.9755
X-int. (-a/b)	8.8891
Dds (1/slope)	273.5

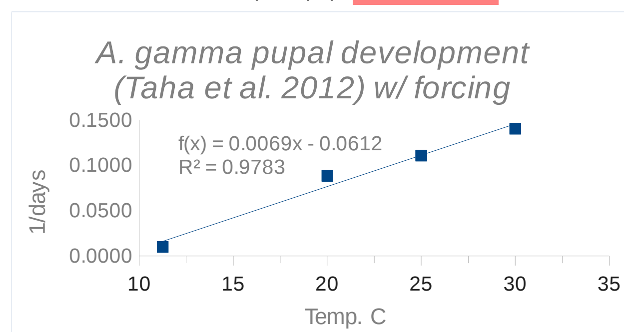
Pupal Development

Temp. C	1/days	pupae
11.2467	0.0101	99
20	0.0883	11.33
25	0.1105	9.05
30	0.1403	7.13

slope	0.0069
Y-intercept	-0.0612
R-sq	0.9783
X-int. (-a/b)	8.8890
Dds (1/slope)	145.2







Egg-to-Adult Development

Temp. C	1/days	days egg-to-adult
9.744	0.0020	500
20	0.0243	41.09
25	0.0316	31.69
30	0.0461	21.71

slope	0.0021
Y-intercept	-0.0188
R-sq	0.9910
X-intercept (-a/b)	8.8892
Dds (1/slope)	473.2

Generation time

Temp. C	1/days	days gen. Time
9.5309	0.0017	600
20	0.0216	46.34
25	0.0280	35.69
30	0.0420	23.81

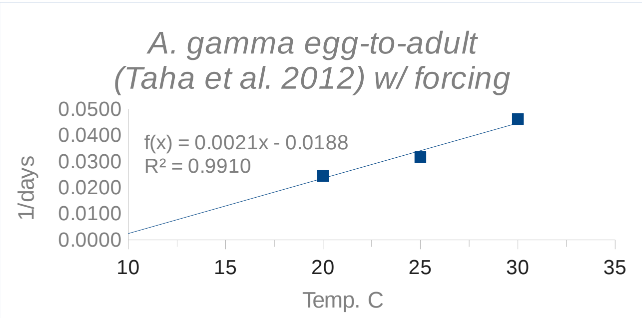
slope	0.0019
Y-intercept	-0.0169
R-sq	0.9873
X-int. (-a/b)	8.8892
Dds (1/slope)	525.1

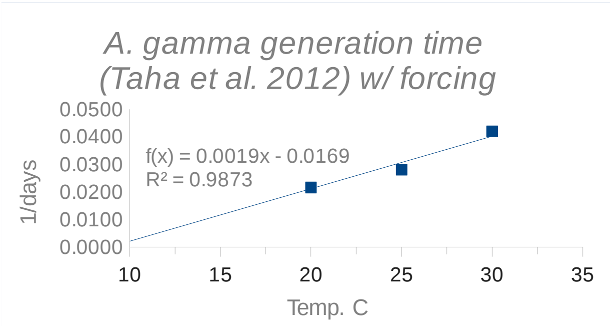
Female longevity

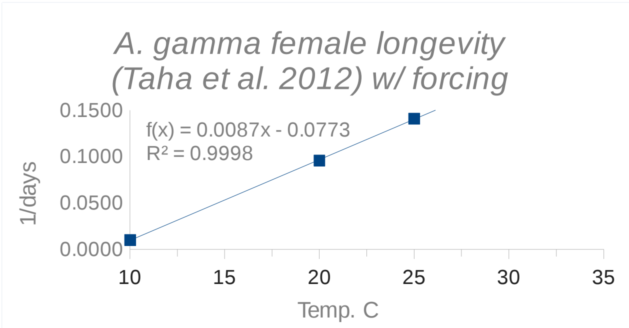
Temp. C	1/days	days female longevity
10.012	0.0101	99
20	0.0957	10.45
25	0.1408	7.1
30		5.2

(drop point at 30C as unrealistically warm)

slope	0.0087
Y-intercept	-0.0773
R-sq	0.9998
X-int. (-a/b)	8.889
Dds (1/slope)	114.9







Results: The forced x-intercept of 8.89C was in accord with Taha et al. (2012) who solved lower threshold values of 10.8, 8.8, 9.4, and 10.3C for larval, egg-to-adult, generation time, and female longevity, respectively. The resulting DD requirements were 53, 273, 145, 473, 525, and 115 DDC for eggs, larvae, pupae, egg-to-adult, generation time, and female longevity, respectively. The value at 30C for female longevity was dropped as unrealistically warm.

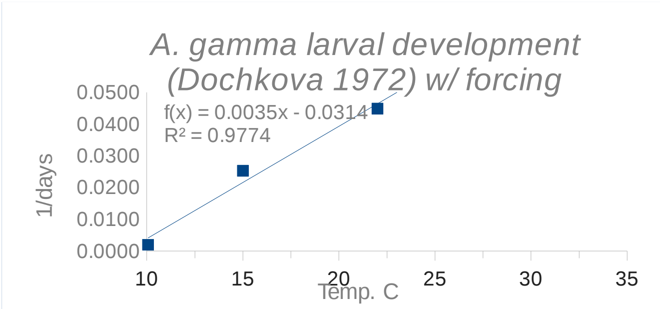
5. Dochkova, B. 1972. Some biological and ecological studies on *Autographa gamma* L. (Lepidoptera: Noctuidae). Rastenievdni nauki (Plant Science). 9(10): 141–149. (Reference used by Nappfast) [in Bulgarian]

- Determine generation time (egg to egg) at 841 DDC using an 8.0C lower threshold
(this would be ca. 790 DDC using an 8.889C lower threshold)

Table 4. Larval development

Temp. C	1/days	days larvae
10.0685	0.0020	500
15	0.0253	39.5
22	0.0448	22.3
30		16.8

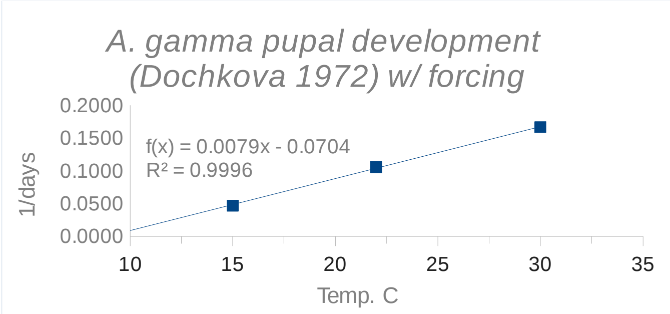
slope	0.0035
Y-intercept	-0.0314
R-sq	0.9774
X-intercept (-a	8.8890
Dds (1/slope	282.7



Note: point at 30C dropped as outlier/likely above linear range of temperature response. A upper dev threshold of 35C therefore seems appropriate.
Note: this result of 283 DD for larval development is high compared to most other sources; leave out of synthesis table.

Table 5. Pupal development

Temp. C	1/days	days pupae
9.064	0.0020	500
15	0.0467	21.4
22	0.1053	9.5
30	0.1667	6
slope	0.0079	
Y-intercept	-0.0704	
R-sq	0.9996	
X-intercept (-a/b)	8.8890	
Dds (1/slope)	126.3	



6. Duthie, D. J. 1983. The ecology of a migratory moth: *Autographa gamma* L. Ph.D. dissertation, Biology Department, Oxford Polytechnic.

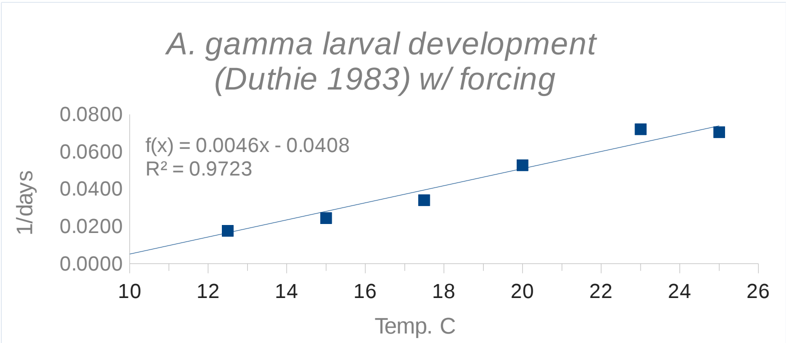
- working with populations that had migrated to England **(**Oxford**)**
- estimated egg development at 4 days at 20C, so ca. 4 * 20-8.889 = 44 DDC (disregard this result as an outlier vs. other studies)
- estimated female longevity at 12 days (range 9.3-12.2) at 20C, so ca. 12 * 20-8.889 = 133 DDC (provided with sucrose solution)
- solved for an overall (larval+pupal devel.) Tlow of 9.3C; found reduced survival at 25C and failure to rear at higher temperatures, also slower larval development at 25C than at 23C; the latter could then be considered “optimal” at least for larvae for this study

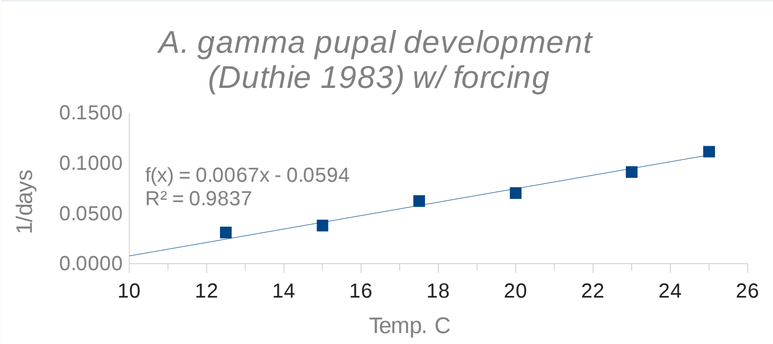
Larval Development

Temp C	1/days	Larval days	
8.947	0.0029	350	
12.5	0.0176	56.9	
15	0.0244	41	
17.5	0.0340	29.4	
20	0.0526	19	
23	0.0719	13.9	
25	0.0704	14.2	
slope	0.0046		
Y-intercept	-0.0408	X-int. (-a/b)	8.889
R-sq	0.9723	Dds (1/slope)	218.10

Pupal Development

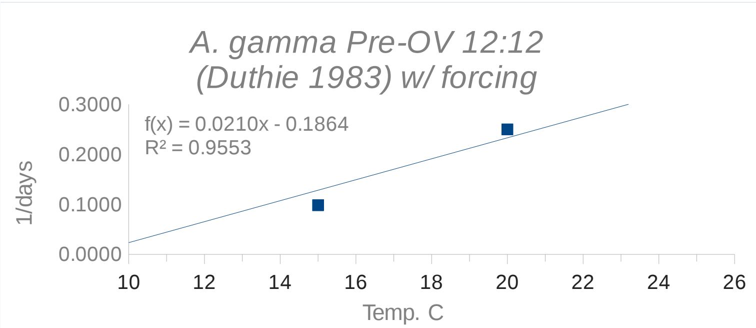
Temp C	1/days	Pupal days	
9.976	0.0033	300	
12.5	0.0309	32.4	
15	0.0377	26.5	
17.5	0.0621	16.1	
20	0.0699	14.3	
23	0.0909	11	
25	0.1111	9	
slope	0.0067		
Y-intercept	-0.0594	X-intercept	8.889
R-sq	0.9837	Dds (1/slope)	149.63





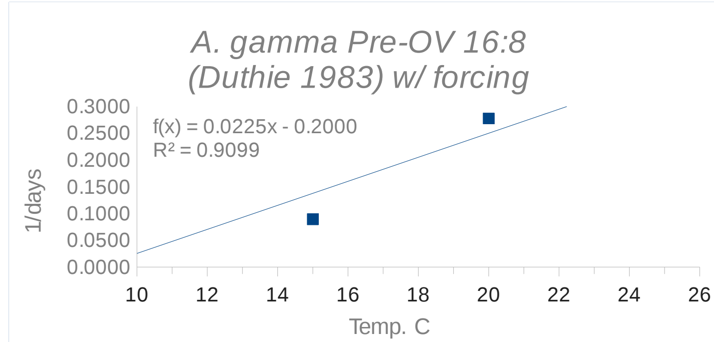
Pre-OV Interval; 12:12 photoperiod (equal)

Temp C	1/days	Pre-OV days	DDC est.	Avg DDC est.
8.503	0.0050	200	(T-Tlow)*days	
15	0.0980	10.2	62	53
20	0.2500	4	44	
25		2.8		
slope	0.0210			
Y-intercept	-0.1864	X-int. (-a/b)	8.889	
R-sq	0.9553	Dds (1/slope)	47.69	



Pre-OV Interval; 16:8 photoperiod (long)

Temp C	1/days	Pre-OV days	DDC est.	Avg DDC est.
8.203	0.0050	200	(T-Tlow)*days	
15	0.0893	11.2	68	54
20	0.2778	3.6	40	
25		2.8		
slope	0.0225			
Y-intercept	-0.2000	X-int. (-a/b)	8.889	
R-sq	0.9099	Dds (1/slope)	44.44	

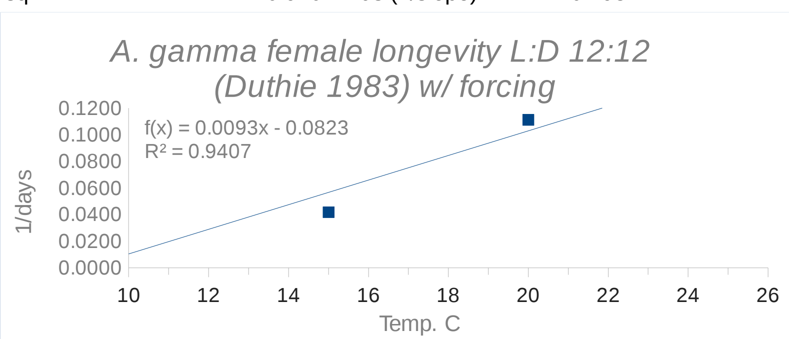


Results: Use average DDC est. from the two temperatures adults are likely to encounter and both equal and long days: 54

Best to not use the constant temperature of 25C for adults, as they are nocturnal and can readily avoid temperatures that shorten their longevity.

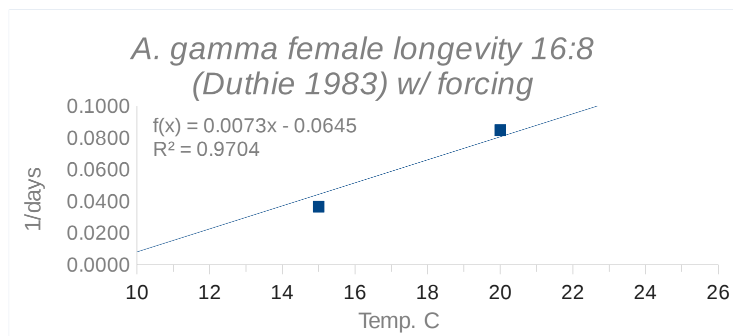
Female longevity; 12:12 photoperiod (equal)

Temp C	1/days	Longev. Days	DDC est.	Avg DDC est.
8.8835	0.0067	150	(T-Tlow)*days	
15	0.0417	24	147	123
20	0.1111	9	100	
25		4.4		
slope	0.0093			
Y-intercept	-0.0823	X-int. (-a/b)	8.889	
R-sq	0.9407	Dds (1/slope)	107.98	



Female longevity; 16:8 photoperiod (long)

Temp C	1/days	Longev. Days	DDC est.	Avg DDC est.
9.304	0.0067	150	(T-Tlow)*days	
15	0.0365	27.4	167	149
20	0.0847	11.8	131	
25		4.6		
slope	0.0073			
Y-intercept	-0.0645	X-int. (-a/b)	8.889	
R-sq	0.9704	Dds (1/slope)	137.89	



Results: Use average DDC est. from the two temperatures adults are likely to encounter and both equal and long days: 136

Best to not use the constant temperature of 25C for adults, as they are nocturnal and can readily avoid temperatures that shorten their longevity.

Overall results: Reared at 6 temperatures, larval and pupal development required 218 and 150 DDC, respectively. At 2 of 3 temperatures, 54 and 136 DDC were estimated for Pre-OV and female longevity, respectively. At 20C, 44 DDC was estimated for egg development (short compared to all other studies available).

7. Comparison / synthesis of above results

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

Source	Country	Egg	Larvae	Pupae	Egg-to-adult	Pre-OV	Female longevity	Approx. Mid-OV[1]	Egg-to-Egg assume 1st OV	Full Gen. assume ca. mid OV
1. Honek et al. 2002	Czech Rep.		222							
2. Hill and Gatehouse 1992	England	53	254	130	437	64	199	133	500	570
3. Harakly 1975	Egypt	52	247	102	401	56	147	130	458	531
4. Taha et al 2012	Egypt	53	274	145	473	52	115	141	525	614
5. Dochkova 1972	Bulgaria	54		126						
6. Duthie 1983	England	53	218	150	421	54	136	119	475	540
Avg of observed (or detn. by add. or subtr.)		**53**	**243**	**131**	**427**	**56**	**149**	**129**	**489**	**556**

[1] Estimate mid or peak oviposition (for full generation time estimates) by adding pre-OV time to 40% of (female longevity – pre-OV).

Note: the Pre-OV and adult longevity estimates are from non-migrating (laboratory reared) adults, and thus should be considered minimum periods.

8. Evidence of springtime flight & Generation time DDs

8a. Estimates based on above phenology results

Nominal migration time (assuming a minimum time between adult emergence and first capture in traps): ca. 3 days at 20C:	33	DDC
First spring flight (assuming that the oldest OW stage are new prepupae): prepupal (12 DD) + pupal devel + the nominal migration time:	176	DDC after Jan 1
First spring flight (assuming that the peak OW stage is mid-instar larvae): 0.5 x larval dev. + pupal + nominal migration time:	285	DDC after Jan 1
Peak spring flight (assuming that the peak OW stage is mid-instar larvae): 0.5 x larval dev. + pupal + ca. 50% female longevity:	327	DDC after Jan 1

8b. Duthie (1983). In England (Oxford ca 50m NW of London)

- Both trapping data and overwintering success trials resulted in moths emerging or trapped by late May (use May 25)
- First and second trapping peaks mid-June to mid-Sept so compare gen time to DDs Jun 15-Sept 15

DDs from degreedays.net (only last 36 months available; Tlow=9C)

	Jan 1- May 25 Dds			Jan 1- June 15 Dds			Jan 1 - Dec 31 Dds			Jun 15 – Sept 15 Dds		
	2018	**2019**	**2020**	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**
Oxford (EGUB)	183	245	194	341	278	372	1385	1233	1268	829	769	678
High Wycombe (03660)	165	291	191	301	228	303	1256	1065	1064	782	701	596
Avg (2 sites, 3 years):		212			304			1212			726	

Results: Average degree-days by end of May (approx first flight) is ca. 212 DDC; DD by Jun 15 (ca. Peak flight) avg of 304 DD; average mid-June to mid-Sept of 726 DDC vs lab study average generation time of ca. 556 DDC. Average DDC for entire year was 1212 DDC: 1212/556 = 2.2 gen/year; so max of 2 gen.s possible for Oxford, England

8c. Dochkova (1972). In Bulgaria, overwinters as late-instar larva or pupa, and has 3 full plus 1 partial generation per year

Compare 3+ a parial gens/yr with actual DDs using available data from DegreeDays.net:

Station	2018	2019	2020	Avg	Gen DDs	Est Gen/yr	Avg.
15549 Razgrad	2161	2200	2070	2144	556	3.9	
LBBG Burgas	2434	2535	2349	2439	556	4.4	
LBPD Plovdiv	2485	2514	2472	2490	556	4.5	4.2

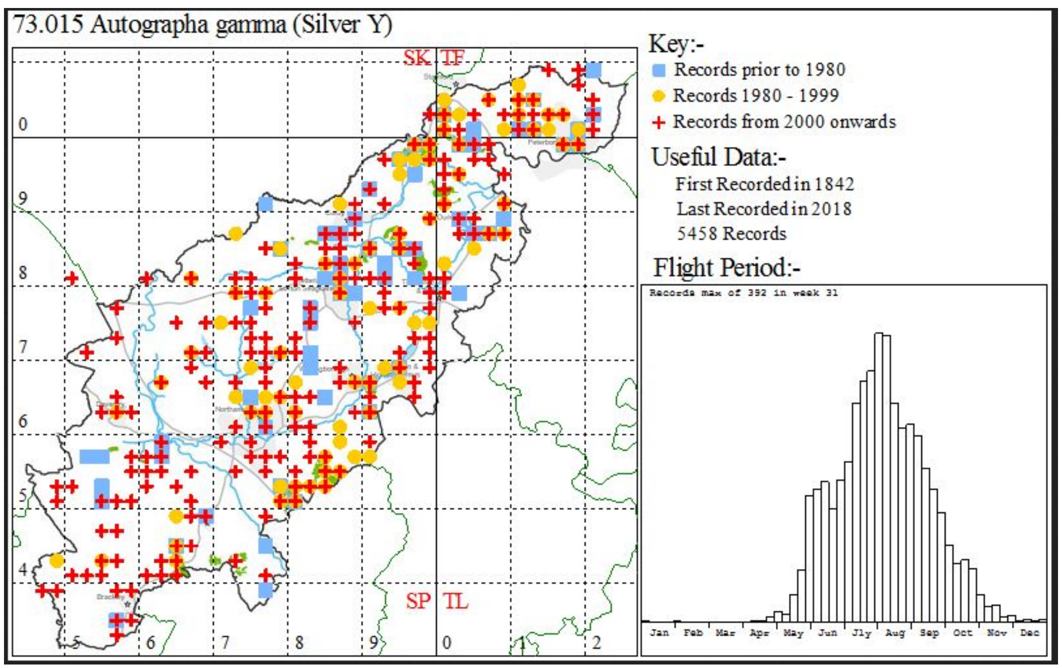
Results: An average potential no. generations per year using full year data was ca. 4.2 gens/year. Considering climate change since 1972 and discounting early spring and late fall DD accumulations, the DD/gen estimate of 556 seems to be in good accord with results of this study.

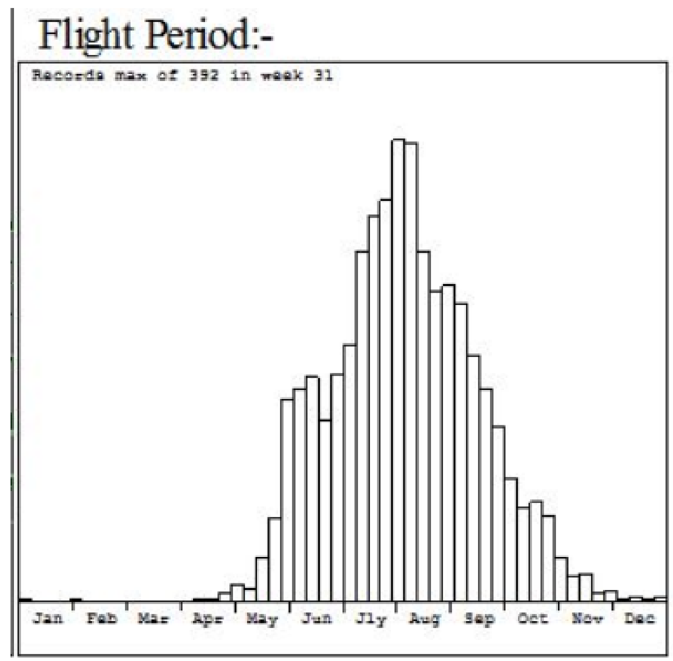
8d. Harakly (1975). in Egypt , flight occurs all winter (Oct-May), with greatest intensity from Nov-Feb; absence of adults and larvae from May-Sept suggests northward migration

Results: This is in accord with other results that migrating adults could arrive in Northern latitudes beginning in April or May and continuing much later in the season.

8e. Moths of Northamptonshire (England) – Silver Y moth; http://www.northamptonshiremoths.org.uk/2441.htm

(light trap based) Flight period from April to November, usually peaking in late summer





- With such an extensive record of flight, it appears that:
1) Significant flight rare before end of May; May 25 looks like a good “first flight” average date to use at least for years with early/warm springs.
2) Difficult to determine a first generation flight peak, but Jun 21 would be a possibility
3) Also difficult to observe separate generational flight peaks, but can do a degree-day analysis from, say June 7 to later dates to predict local generation turnover.

DDs from degreedays.net (only last 36 months available) (Tlow = 9C):

	Jan 1- May 25 DDs			Jan 1- Jun 21 Dds			Jun 7 – Aug 31 Dds			Jun 7 – Oct 15 Dds		
Northamptonshire	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**
EGGW	175	169	208	360	294	360	797	695	606	1028	897	793
Birmingham (EGBB)	183	182	212	375	299	372	784	665	617	1007	872	823
Avg (2 sites, 3 years):		188			343			694			903	

Results: Keeping in mind that these flight data can possibly reflect both migration and local overwintering (southern states), a May 25 avg total of 188 DD and a Jun 21 avg total of 343 DD provide first and peak flight estimates for this section of England (ca. 50m N. of London, or Central England). It apears that an avg DD total of 694 DD between Jun 7 and Aug 31 and 903 DD between Jun 7 and Oct 15 allows for only a single full generation to develop, perhaps two maximum before the presumed return flight to the south in the fall.

8f. Summary of OW generation flight evidence:

<u>Source</u>	First flight <u>(ow prepupae)</u>	First flight <u>(ow mid-larvae)</u>	Peak flight <u>(ow mid-larvae)</u>
8a. Estimates based on phenology results	176	285	327
8b. Duthie 1983	212		304
8e. Moths of Northamptonshire	188		343
avg of 8b and 8e	200		324

Results: The degree-day analysis of trapping reports from Duthie (1983) and Moths of Northamptonshire (website) both tend to support assumptions that first moths arrive at times (avg 200 DD) similar to pupal development plus a nominal flight time (ca. 176 DD), and peak first gen. flight (ca. 324 DD) corresponds with ½ larval + pupal + ½ adult longevity (ca. 327 DD). We will use the average flight trapping data from the two reports from England (200 and 324 for first and peak flight, respectively).

8g. Data from Italy to compare with flight phenology estimates:

Burgio, G. and Maini, S. (1994): Phenylacetaldehyde trapping of *Ostrinia nubilalis* (Hb.), *Autographa gamma* (L-) and hoverflies: trap design efficacy. Boll. Ist. Ent. “G. Grandi” Univ. Bologna, 49, 1–14.

- A. gamma 1991 N. Italy trap peaks June 13 and July 25 Note: assume climate change has moved these dates 7 and 10 days earlier: June 6 and July 15.

Dds from degreedays.net (only last 36 months available) (Tlow = 9C):

	Jan 1- Jun 6 DDs			Jan 1- Jul 15 DDs		
Bologna Italy	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**
LIPE	686	566	662	1247	1193	1226
Parma (LIPX)	672	523	631	1235	1176	1171
Avg (2 sites, 3 years):		623			1208	

Results: First peak flight is ca. 300 DD later than for England; which may indicate that: As moths are capable of long distance flight in just a few days, this species may arrive at roughly the same time throughout Europe from overwintering locations to the South. This might mean that a calendar date could be a better indicator of model initiation than DDs (i. e. use a calendar date biofix). However, we have insufficient data to derive such a biofix.

As our presumptive model should be conservative (and not under-predict first flight), we will not include this result in the model.
Note: still trying to obtain the original article to verify trapping start dates; it could be that they put up traps too late to pick up an earlier flight peak.

9. Notes, comments from misc. sources

- Under short day photoperiods, pre-oviposition interval is increased (Hill and Gatehouse 1992)
- Overwinter as larvae, no true diapause, but slowed devel due to low food quality (Saito 2007, Honek 2002)
- Pupation is above-ground on host plants (Hill and Gatehouse 1992)
- (Light trap based) A. gamma flight time of day – most abundant 6pm-midnight; some moths captured through 4am (Nowinszky et al 2007. Appl. Ecol. and Environ. Res. 5:103-107 Hungary)
- Able to migrate N or S around 500miles/night, start at dusk, flying all night (Chapman et al. 2008. Current Biology 18:514-518)
- like A. californica (alfafa looper), this species reported to be heavily impacted by parasitoids and viral diseases (Dochkova 1972, Venette et al. 2003)

Phenology Model Summary:

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

	Deg. C	Deg. F	
Lower devel. threshold	8.889	48	
Upper devel. threshold	35	95	
Event	**DDC**	**DDF**	**Notes**
First moths OW gen.	200	360	results from Duthie (1983) & Northamptonshire England
Peak flight OW gen.	324	582	results from Duthie (1983) & Northamptonshire England
Peak egghatch 1st gen.	433	780	Peak flight+PreOV+egg devel.
First moths 1st gen.	756	1,360	Frist OW moths + gen. Time
Peak flight 1st gen.	879	1,583	Peak flight + gen. time
Peak egghatch 2nd gen.	989	1,780	
Peak flight 2nd gen.	1,435	2,583	
Peak egghatch 2nd gen.	1,545	2,780	
Peak flight 3rd gen.	2,100	3,781	
Peak flight 4th gen.	2,656	4,781	

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

	DDC		DDF	
Event	**(begin)**	**(end)**	**(begin)**	**(end)**
Pre-first moths	0	199	0	358
OW gen. Flight activity	200	511	360	919
1st gen. Larval activity	309	755	557	1,358
1st gen. Flight activity	756	1,066	1,360	1,919
2nd gen. Flight activity	1,311	1,622	2,360	2,919
3rd gen. Flight activity	1,867	2,178	3,360	3,920
4th gen. Flight activity	2,423	2,733	4,361	4,920

DDRP OW Parameters:		**DDC**	Notes
distro_mean	average DDs to OW larvae first pupation	160	Base on first OW flight minus (nominal migration time plus pupal devel. time)
distro_var	variation in DDs to OW larvae first pupation	5000	
xdist1	minimum DDs (°C) to OW larvae first pupation	36	Based on peak OW flight minus (nominal migration time plus pupal devel. time)
xidst2	maximum DDs (°C) to OW larvae first pupation	231	Based on very young OW larvae present
distro_shape	shape of the distribution	normal	

CLIMATE SUITABILITY MODEL

Note: no previous climatic suitability modeling studies. Venette et al. (2003) is the only known risk assment for CONUS.

Venette, R. C., E. E. Davis, H. Heisler, and M. Larson. 2003. Mini risk assessment silver Y moth, *Autographa gamma* (L.) [Lepidoptera: Noctuidae]. Cooperative Agricultural Pest Survey, Animal and Plant Health Inspection Service, US Department of Agriculture.

- Assessed risk based on matching biomes between native range and CONUS
- This map looks very different than risk based on the CLIMEX and DDRP climatic suitability analysis

1. **Ecological Suitability. Rating: High.** *Autographa gamma* is found throughout the Palearctic. This region largely has a dry or temperate climate (CAB 2003). The currently reported global distribution of *A. gamma* suggests that the pest may be most closely associated with deserts and xeric shrublands; montane grasslands [not in the US]; and temperate broadleaf and mixed forests. Consequently, we estimate that approximately 48% of the continental US would be suitable for *A. gamma* (Fig. 2). See Appendix A for a more complete description of this analysis. In suitable areas, *A. gamma* should sustain populations by reproducing locally and overwintering successfully. However, *A. gamma* is a highly mobile pest, capable of both northerly and southerly migrations (Hill and Gatehouse 1992). If this pest migrated as far in the US as it does in Europe and Asia, all potential hosts would be in jeopardy of attack during particular times of the year.

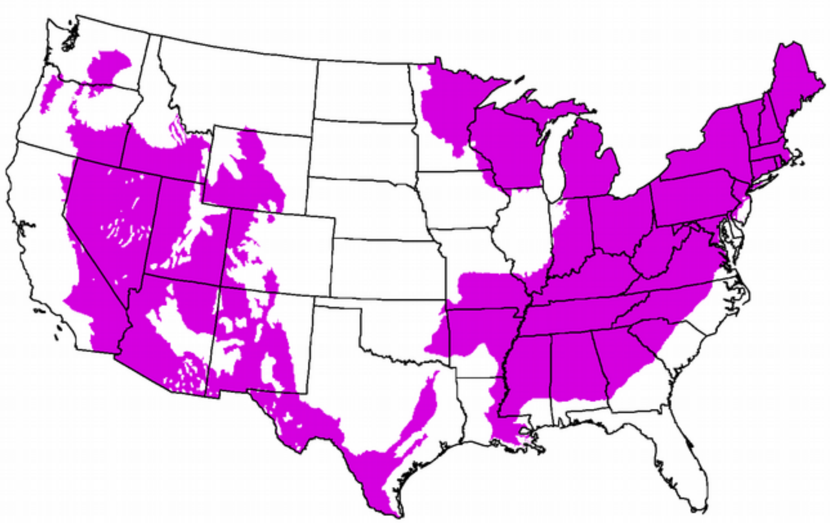


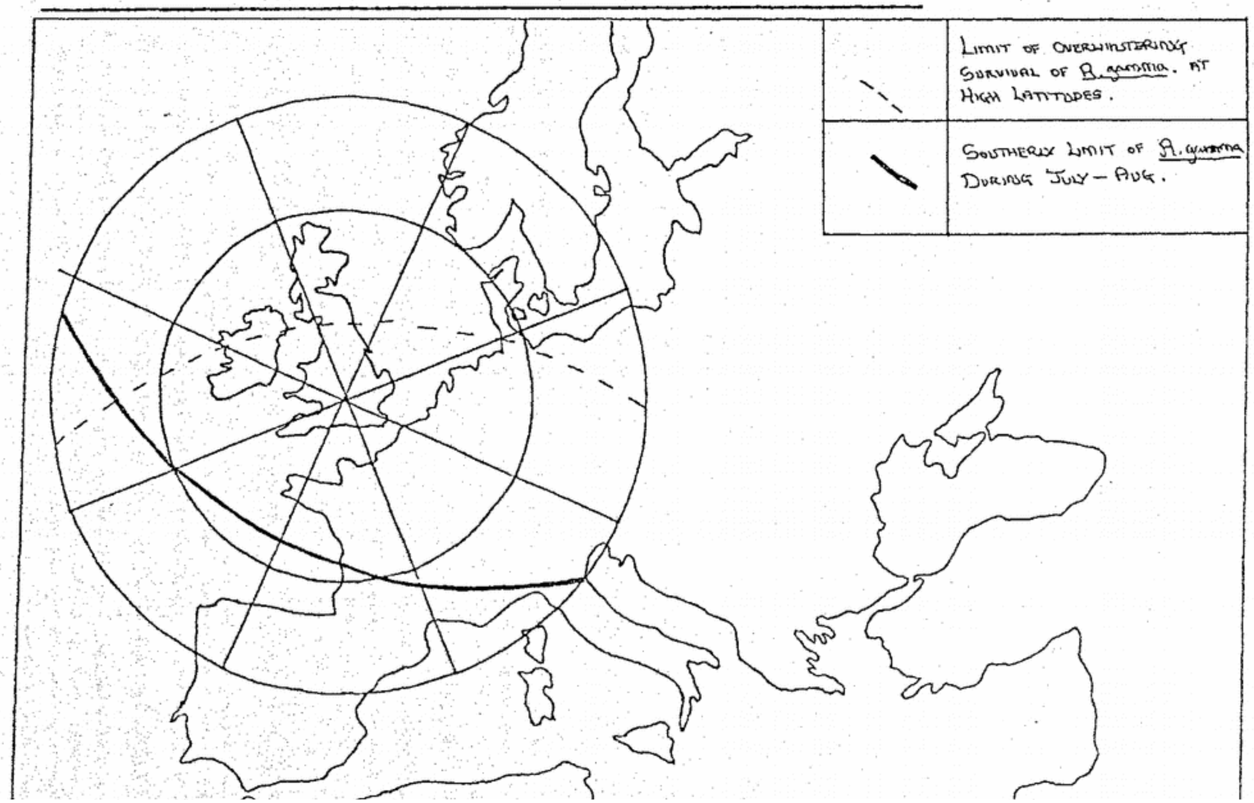
Figure 2. Predicted distribution of *A. gamma* in the continental US.

Sources of data for CLIMEX model fitting

1. Duthie, D. J. 1983. The ecology of a migratory moth: *Autographa gamma* L. Ph.D. dissertation, Biology Department, Oxford Polytechnic

- Presented a map of the geographic limit to OW survival
- Concluded that survival probability of moths north of 48N is appreciably lower than in southern regions of Europe and Mediterranean
- The southern limit in the map indicates that immigration from diminished southern pops in Jul-Aug would contribute little to northern pops during that time
- Reported significant reductions in survival of larvae and adults at temps >23C, and adult survival is lower at temps <15C

APPENDIX A: Map used for the flight direction model of A.gamma adults.



2. Locality records from GBIF in its native range (2 June 2020; GBIF Occurrence Download https://doi.org/10.15468/dl.hje3bv)

- Records did not have information on whether population was seasonal or permanent

3. Additional references for locality records or other data from the coldest and hottest parts of the species' distribution

Region	Country	Source	Description
Middle East	Iran	Zahiri & Fibiger (2008) SHILAP Rev. de Lepidopt.	Plate 26 depicts occurrence records throughout Iran
	Saudi Arabia	El-Hag et al. (1991) Crop Protection	Gassim region
	Israel	Yathom & Rivnay (1968) Z. Angew. Entomol.	Occurrence records for Israel
	Iraq	Younis et al. (1988) Mesopotamia J. of Agriculture	30 km S of Mosul
	United Arab Emirates	Gillett (2007) Tribulus	Al Muwaiji
	Pakistan	Shakira et al. (2011) Fuuast J. Biol.	Sindh and Azad Kashmir
Africa	Ethiopia	Kravchenko et al. 2015. Zootaxa	Distributed throughout Ethiopia except for tropical lowlands
	Libya	Yahiya (2014) Middle East J. Agric. Res.	Al-Jabal Al-Khdar
	Algeria	Soldan & Spitzer (1983) Acta Soc. Entom. Bohem.	Mitidja Basin
		Samira et al. (2020) Zootaxa	Theniet El Had National Park
	Egypt	Rouma (2018) J. Plant Prot. and Path., Mansoura Univ.	Distributed throughout all of Egypt
Europe	Belinux countries	Tornianen et al. (2018) Ecol. Entomol.	Overwinters
	Germany	Tornianen et al. (2018) Ecol. Entomol.	Overwinters
	Czechia	Novak (1968, 1972) - see Saulich et al. (2017)	Overwinters
	Finland	Kaisila (1962) Acta Entomologica Fennica	Small resident population reportedly overwinters
	United Kingdom	Duthie (1983) PhD dissertation	Species not known to overwinter in southern UK
Asia	Japan	Saito (2007) Appl. Entomol. Zool.	May overwinter on host plants under snow

4. Torniainen, J. and L. Mikonranta. The origins of northern European *Autographa gamma* individuals evaluated using hydrogen stable isotopes. Ecological Entomogy 43:699-702.

- Used stable isotope analysis to infer the origins of summer migrants in Finland
- Found clear differences between origins of spring and autumn generations; the spring gen had a more southern origin
- The autumn gen probably originated from central Europe (Benelux countries, Germany, parts of France)

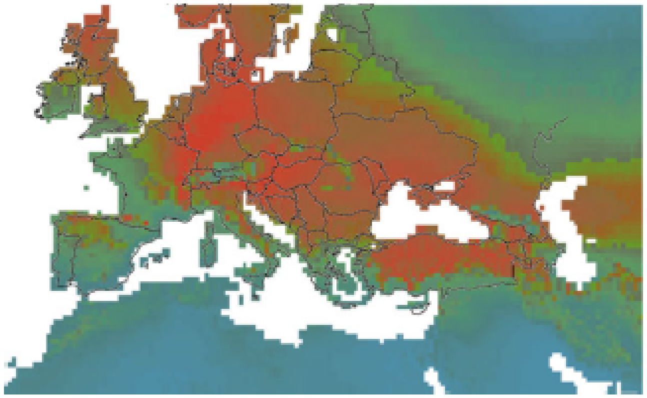


Fig. 2. Estimated origin of spring generation *Autographa gamma* caught in Finland. The assignment is based on comparison of hydrogen stable isotopes of annual precipitation (δ^2H_p) and adult wing material (δ^2H_w). Red, high probability of origin; blue, low probability of origin. [Colour figure can be viewed at wileyonlinelibrary.com].

5. Saulich, A., I. Sokolova, and D. Musolin. 2017. Seasonal cycles of noctuid moths of the subfamily Plusiinae (Lepidoptera, Noctuidae) of the Palaearctic: Diversity and environmental control. Entomological Review 97:143-157.

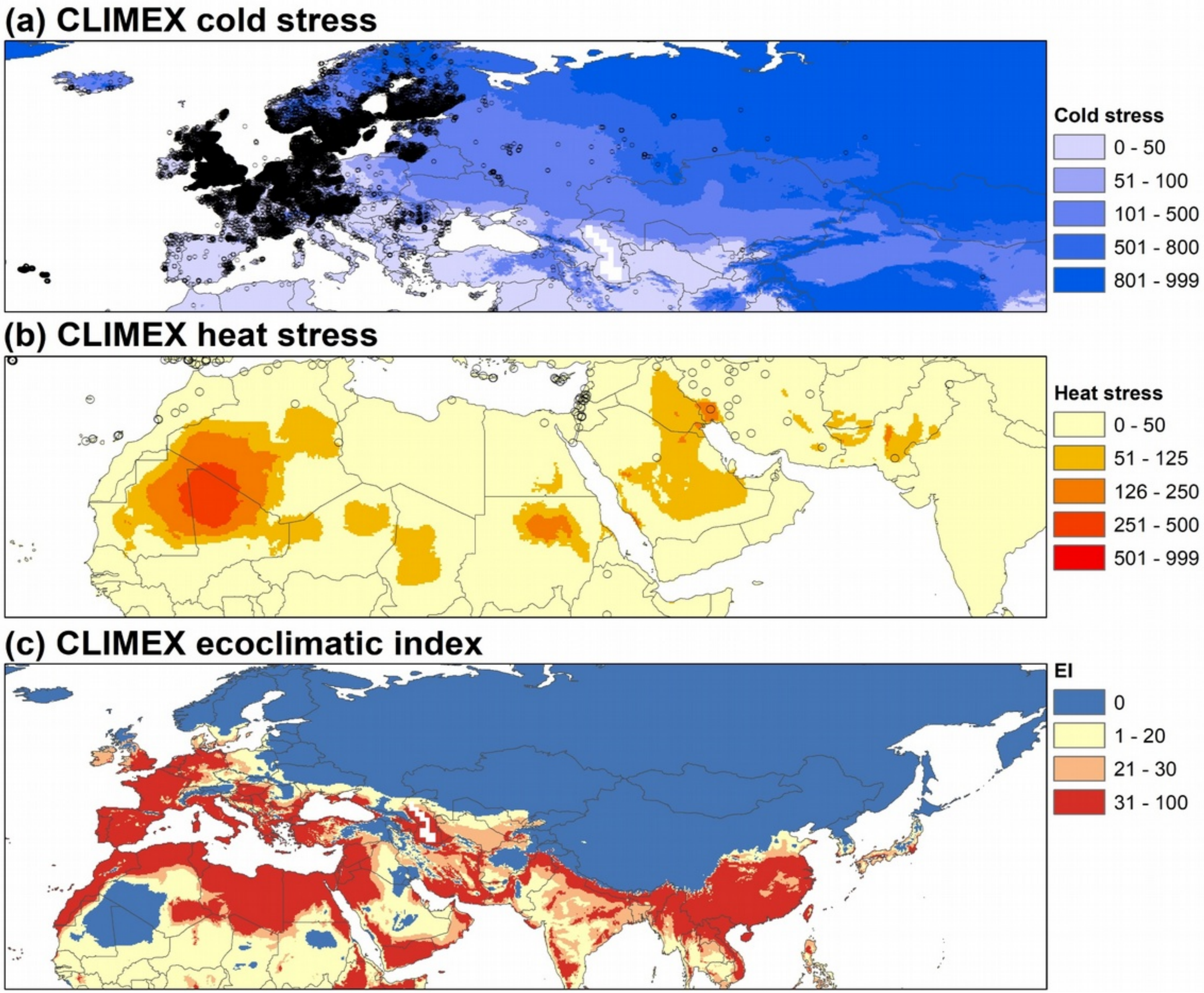
- Provides a good review of previous work on the climatic tolerances of *A. gamma*
- Species can overwinter in Hokkaido, Japan, after entering a "diapause-like prolongation of larval duration" (see Saito 2007, Appl. Entomol. Zool)
- In the studies on Japan pops, 1.4% of 660 tested larvae survived at 0C for 4 months
- Survival of Hokkaido pops may be facilitated by snow cover, which reduces the effects of below-zero temps
- Experimental assessment of larval cold tolerance showed their supercooling temp is as low as -22C (studies by Novak, 1968, 1972)
- Eggs and pupae have a rather high cold tolerance (up to −30.0°C and −12.0°C, respectively)
- At least in Europe prolonged overwintering is limited by the absence of dedicated energy reserves
- Northernmost pops that survive winters are small; large increases in abundance when migrants arrive

6. CLIMEX model (this study; see white paper for more details)

- Used locality data from GBIF and literature to help with model fitting (see below)
- Areas with an EI > 20 were considered to be suitable for long-term persistence
- Conversely, areas with an EI < 20 may support only temporary establishment during the growing season after migration events
- The locations of areas with EI > 20 vs. EI < 20 are mostly consistent with reports of the species' permanent vs. temporary distribution
- However the species is not known to overwinter Denmark and southern Sweden (which had EI > 20)
- Unclear whether this is an overprediction, because Kaisila (1962) Acta Entomol. Fennica reports an OW population in Finland
- Also Saito (2007) reports OW larvae in Hokkaido, Japan, as noted above

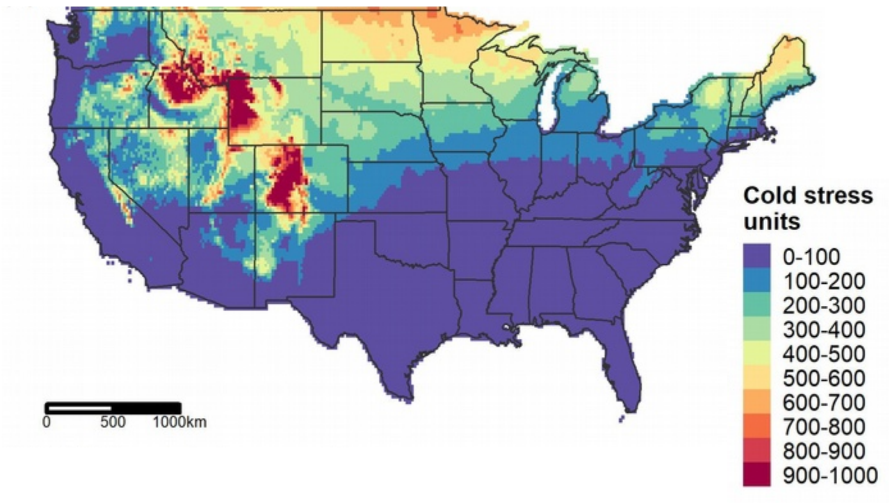
Final CLIMEX parameters			
Moisture Index			
SM0	SM1	SM2	SM3
0.05	0.1	1	2
Temperature Index			
DV0	DV1	DV2	DV3
8.9	15	23	35
Cold Stress			
TTCS	THCS		
-1	-0.0015		
Heat Stress			
TTHS	THHS		
38	0.0015		
Dry Stress			
SMDS	HDS		
0.05	-0.0001		
Wet Stress			
SMWS	HWS		
2.5	0.002		
Degree-days per Generation			
PDD			
556			

Maps of cold stress, heat stress, and the ecoclimatic index in the native range

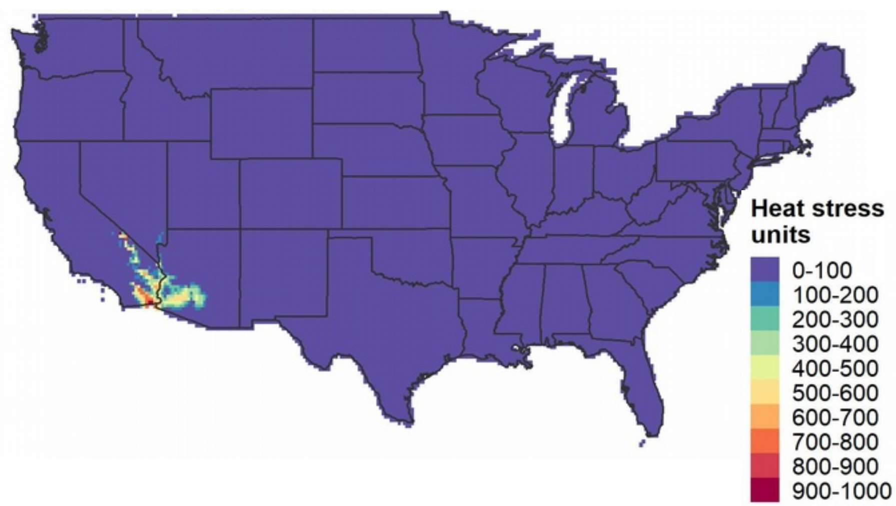


CLIMEX results for CONUS

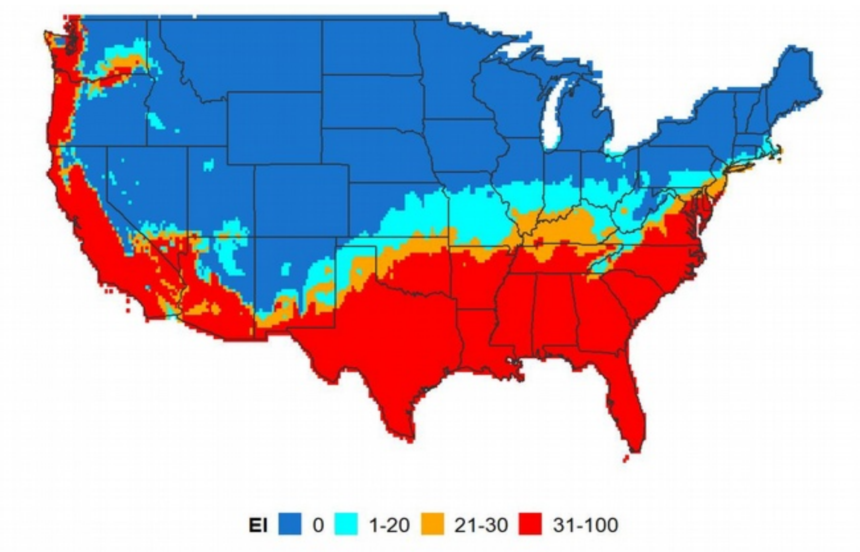
CLIMEX Cold Stress (CONUS)



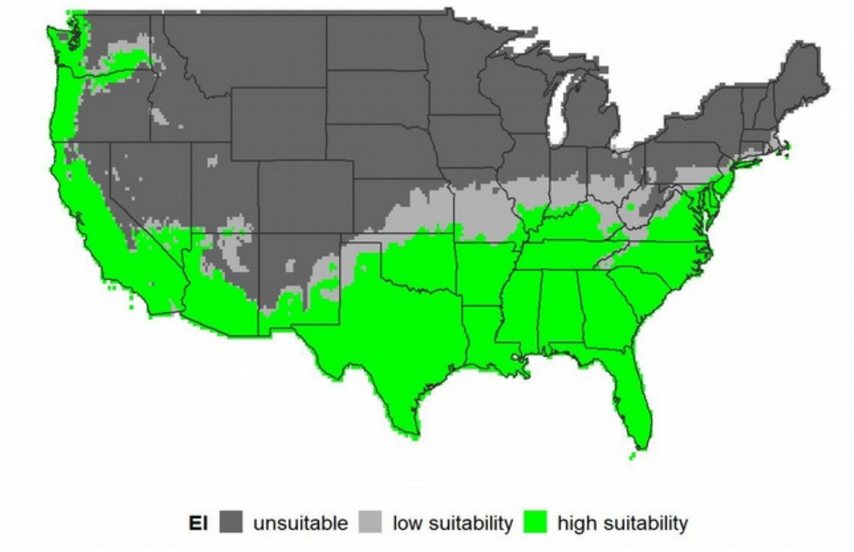
CLIMEX Heat Stress (CONUS)



CLIMEX Ecoclimatic Index (EI)



Map where EI = 0 is unsuitable, EI < 20 = low suit., EI > 20 = high suit.

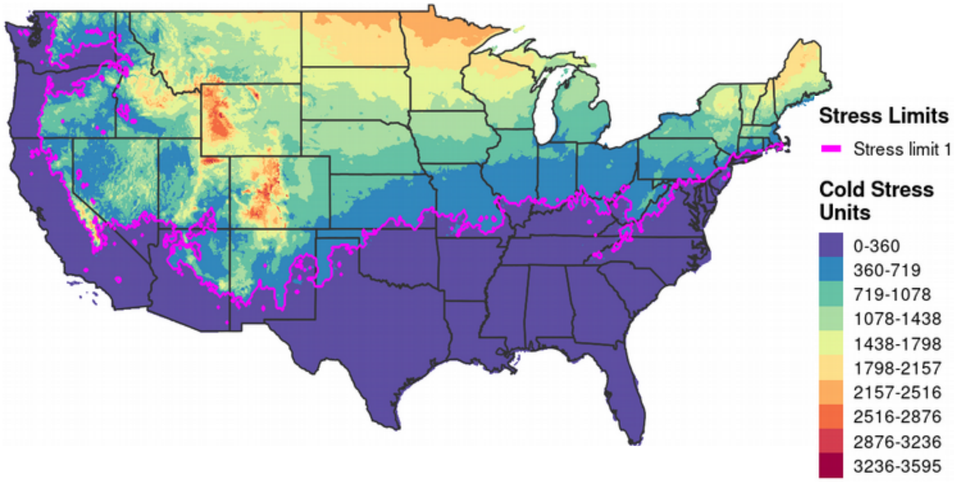


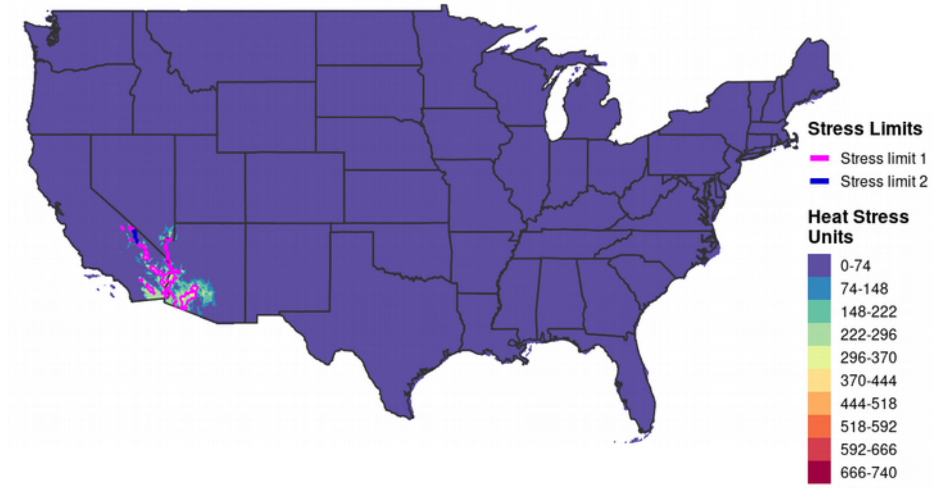
7. DDRP climate suitability model (this study)

- Developed in accordance with CLIMEX model results
- Analysis used daily downscaled 1961-1990 normals to match time scale of CLIMEX
- Value for cold stress limit2 is difficult to assign because the species can migrate all the way to Greenland; used highest possible cold stress value for CONUS (=3600)
- Areas under moderate stress exclusion by cold stress (cold stress > limit1) represent zones for temporary establishment after annual migrations
- Some areas in the desert Southwest may be too hot for long-term establishment (heat stress > limit 2)
- Given evidence that species may overwinter in Finland and Hokkaido, Japan, then cold stress parameters may be too stringent

DDRP Cold Stress	Value	Units
cold stress threshold	-1	C
limit 1 (mod. cold stress)	375	DDC
limit 2 (sev. cold stress)	3600	DDC

DDRP Heat Stress	Value	Units
heat stress threshold	38	C
limit 1 (mod. heat stress)	260	DDC
limit 2 (sev. heat stress)	600	DDC





DDRP All Stress Exclusion