Phenology/Degree-Day and Climate Suitability Model Analysis – Updates Feb. 2023

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Emerald ash borer ***Agrilus planipennis*** **Fairemaire (Coleoptera: Bupestridae)**

Hosts: ash trees (*Fraxinus* spp.) Native to: East Asia (China, Japan, Korea and Far East Russia)

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

Adult beetle

Early and late instar larvae

Larval galleries

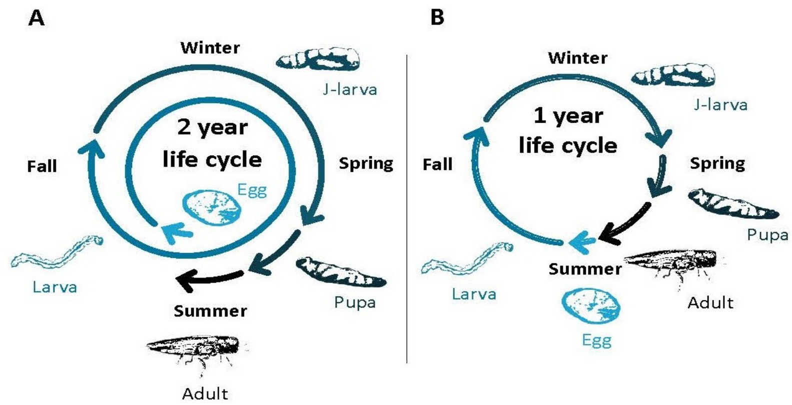
Thresholds, degree-days and events used in Emerald ash borer model:

Parameter abbr.	**Description**	**degF**	**degC**	**DDF**	**DDC**	
eggLDT	egg lower dev threshold	54	12.2	-	-	
eggUDT	egg upper dev threshold	97	36.0	-	-	
larvaeLDT	larvae lower dev threshold	54	12.2	-	-	
larvaeUDT	larvae upper dev threshold	97	36	-	-	
pupaeLDT	pupae lower dev threshold	54	12.2	-	-	
pupaeUDT	pupae upper dev threshold	97	36	-	-	
adultLDT	adult lower develpmental threshold	54	12.2	-	-	
adultUDT	adult upper dev threshold	97	36	-	-	
eggDD	duration of egg stage in DDs	-	-	310	172	
larvaeDD	duration of larvae stage in DDs	-	-	1260	700	
pupaeDD	duration of pupae stage in DDs	-	-	243	135	
adultDD	duration of pre-OV plus time to 50% OV	-	-	260	145	
OWlarvaeDD	DDs until OWlarvae complete their development	-	-	varies	varies	
eggEventDD	DDs into egg stage that eggs begin hatching	-	-	310	172	
larvaeEventDD	DDs into larvae stage when J-larvae form	-	-	878	488	*See note below
pupaeEventDD	DDs until end of pupal stage	-	-	243	135	
adultEventDD	DDs into adult stage when 1st oviposition occurs	-	-	130	72	
coldstress_threshold	cold stress threshold	-23.8	-31	-	-	
coldstress_units_max1	cold degree day limit when most individuals die	-	-	144	80	
coldstress_units_max2	cold degree day limit when all individuals die	-	-	288	160	
heatstress_threshold	heat stress threshold	100.4	38			
heatstress_units_max1	heat stress degree day limit when most individuals die	-	-	135	75	
heatstress_units_max2	heat stress degree day limit when all individuals die	-	-	270	150	
distro_mean	average DDs to OW larvae first pupation	-	-	378	210	
distro_var	variation in DDs to OW larvae first pupation	-	-	27000	15000	
xdist1	minimum DDs (°C) to OW larvae first pupation	-	-	135	75	
xidst2	maximum DDs (°C) to OW larvae first pupation	-	-	630	350	
distro_shape	shape of the distribution	-	-		lognormal	

*Increased larvaeEventDD from 549 to 700 DDCs to decrease extent of underprediction of this event (see Barker et al. 2023)

Life cycle of A. *planipennis*

- EAB has a 1 year life cycle at warmer latitudes vs. a 2-yr cycle at higher latitudes
- The two and one year life cycle of EAB (from Pellecchia 2020, thesis)
- J-larvae (prepupae) undergo an obligatory diapause that requires ≥ 2 mo of at least 12.8C to exit (Duan et al. 2020)



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PHENOLOGY MODEL ANALYSIS

A) Analysis of temperature-development data

A1. Duan, J. J., T. Watt, P. Taylor, and K. Larson. 2013. Effects of ambient temperature on egg and larval development of the invasive emerald ash borer (Coleoptera: Buprestidae): implications for laboratory rearing. Journal of Economic Entomology 106:2101-2108.

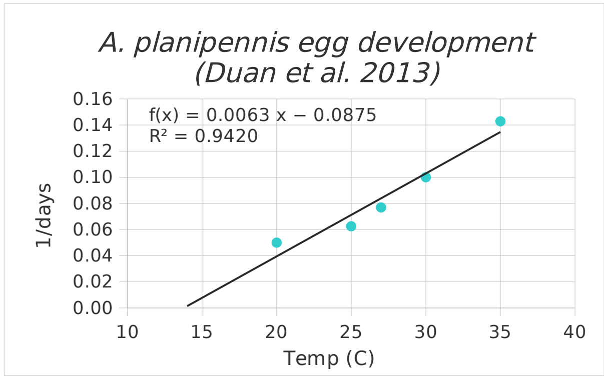
- Conducted temp-development study of eggs and larva, derived from a population in Maryland
- Summarized egg data from Table 1 (median time for egg hatch) and larvae data from Table 2 (mediate time for reaching mature J-larva)
- Summarized egg to J-larvae data from Table 2 (median values)
- Calculated development rate for value at forced x-intercept using regression equation
- Reported adverse effects at 35C for larvae but not eggs; bark should insulate larvae by at least 2-4 degrees C so Tlow should be between 34-38; assume 38 would work well
- Optimal range of temps are suggested to be 25-30C

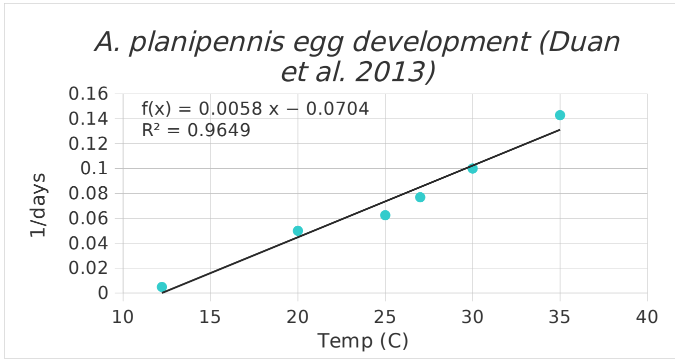
Egg development (no forcing)

Temp C	Temp F	Days	1/days
20	68	20.0	0.0500
25	77	16.0	0.0625
27	80.6	13.0	0.0769
30	86	10.0	0.1000
35	95	7.0	0.1429
		slope	0.0063
		intercept	-0.0875
		R-sq	0.9420
		Tlow (-a/b)	13.8
		DD req. (1/slope)	157

Egg development (w/ forcing)

Temp C		Days	1/days
12.22		205	0.00487804878
20		20.0	0.0500
25		16.0	0.0625
27		13.0	0.0769
30		10.0	0.1000
35		7.0	0.1429
		slope	0.0058
		intercept	-0.0704
		R-sq	0.9649
		Tlow (-a/b)	12.22
		DD req. (1/slope)	174





Egg to J-larva (no forcing)

Temp C	Days	1/days
20	86	0.0116
25	50	0.0201
27	49	0.0204
30	44	0.0227
35	56	
	slope	0.0011

Egg to J-larva (w/ forcing)

Temp C	Days	1/days
12.82	1700	0.0006
20	86	0.0116
25	50	0.0201
27	49	0.0204
30	44	
35	56	

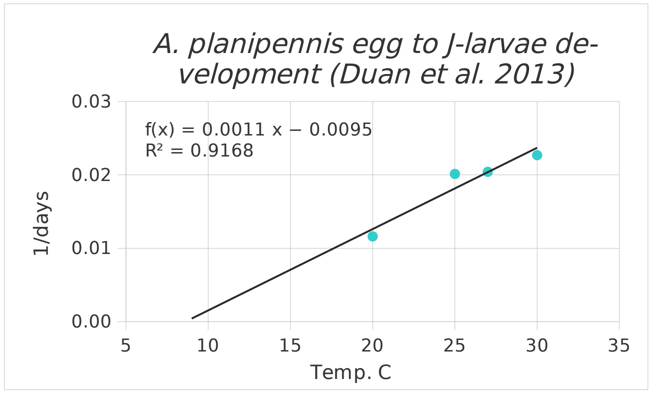
Egg hatch to J-larvae (w/forcing)

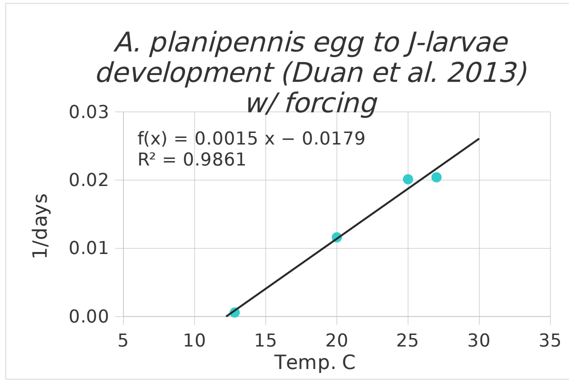
Temp C	Days	1/days
12.54	1700	0.0006
20	66	0.0151
25	34	0.0297
27	36	0.0278
30	34	
35	49	

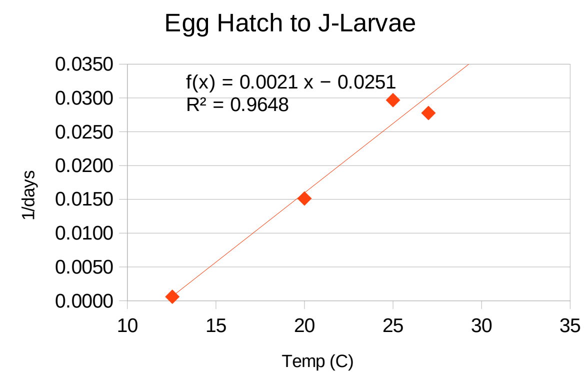
intercept	-0.0095
R-sq	0.9168
Tlow (-a/b)	8.6
DD req. (1/slope)	903

slope	0.0015
intercept	-0.0179
R-sq	0.9861
Tlow (-a/b)	12.22
DD req. (1/slope)	682

slope	0.0021
intercept	-0.0251
R-sq	0.9648
Tlow (-a/b)	12.22
DD req. (1/slope)	488







A2. Duan, J. J., J. M. Schmude, and K. M. Larson. 2020. Effects of low temperature exposure on diapause, develoment, and reproductive fitness of the emerald ash borer (Coleoptera: Buprestidae): implications for voltinism and laboratory rearing. Forest Entomology. https://doi.org/10.1093/jee/toaa252

- Evaluated effect of exposure of diapausing mature 4th instars (J-larvae) to either 1.7 or 12.8C for 1-9 months on post-chill development
- Post-chill experiments quantified adult emergence, longevity, and lifetime fecundity under statandard conditions (26C, 16:8 h L:D)
- Also determined effect of different stages of larvae chilled at 12.8C for 3 mo on post-chill development to adults
- Findings include: **1) Termination of diapause requires 12.8C for at least 2 mo**

  2) Chill treatment of larvae at 1.7C prevents post-diapause development to adults regardless of chill time (1-9 mo)

  3) Chill treatments of immature larvae resulted in few adults, indicating best diapause is as a J-larvae

  4) Emergence rates decrease after about 5 mo at 12.8C due to J-larvae mortality
- Implications: 1) Requirement to be a J-larvae to undergo diapause explains why insects are semi-voltine in some colder areas

  2) J-larve may advance their diapause development when ambient temps in most days are ca. 12.8C

  3) Obligatory diapause begins in late summer/fall and will stay in state of quiescence through entire winter due to low temperatures even if diapause is terminated
- **Interpretation**: A more complex phenology model could incorporate a diapause threshold for J-larvae; this could result in more precise estimates of voltinism because it would estimate whether J-larvae proceed to developing into adults vs. staying in the J-larvae stage through the next winter (semivoltine)

A3. Keena, M. A., J. Gould, and L. S. Bauer. 2009. Factors that influence emerald ash borer *(Agrilus planipennis*) adult longevity and conditions. oviposition under laboratory. Page 81 in Gen. Tech. Rep. NRS-P-51. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 114 p.

- This is a published abstract only - no original data are reported
- They evaluated the effects of host plant, temperature, RH and oviposition substrates on adult survival and fecundity
- Adult longevity decreased as temperature increased from 20 to 30C (consistent with Lyons and Jones 2005)
- Only one female oviposited at 20C, while percentage ovispoiting and fecunidity were higher at 25C than at 20 or 30C
- Egg hatch was also highest at 25C
- Fecundity and surival were highest at 65% RH (lower at 55 and 75% RH)

- Egg hatch lowest at 55% RH

A4. Lyons, D. B., G. C. Jones, and K. Wainio-Keizer. 2004. The biology and phenology of the emerald ash borer. Page 62 in Proceedings, 16th U.S. Department of Agriculture interagency research forum on gypsy moth and other invasive species. GTR-NE-337. U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Annapolis, MD.

- This is a published abstract only - original data are not reported
- Studied adult longevity, oviposition, fecundity and egg development at 24C in the lab
- Unclear if study of adults includes days that adults spend in pupal cell before emergence
- Source populations were from Ontario, Canada
- The Tlow used for DD req was obtained from other studies

Stage	Days	Temp C	Tlow	DDC	DDF	
Egg	36.8	18	12.2	213	384	
Egg	18.4	24	12.2	217	391	
PreOV	22.1	24	12.2	260.8	469.4	← This is hard to believe – a full 22 days between emerg and OV at 24C ???
Longevity	26.5	24	12.2	312.7	562.9	

Results: the DD req for egg stage are higher than data reported by Duan et al. 2013 and most other studies

A5. Lyons, D. B. and G. C. Jones. 2005. The biology and phenology of the emerald ash borer. Pages 62-63 in Proceedings, 16th U.S. Department of Agriculture interagency research forum on gypsy moth and other invasive species. GTR-NE-337. U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Annapolis, MD.

- This is a published abstract only - no original data are reported
- They studied the emergence of adults in Essex Co., Ontario in 2003 and 2004, and studied development and longevity in lab
- Constant temperatures are assumed do to be 18, 21, 24, 27, 33 and 35C (this was used for the longevity study)
- Male and female data were report for pre-pupae, pupae, and teneral adult (only female data are shown below)
- For temps > 18C, longevity (median days) was inversely correlated with temperature
- DD units were not reported for longevity, so used a Tlow of 12.2C
- "Prepupae" are J-larvae that were extracted from trees in the winter after a chilling period

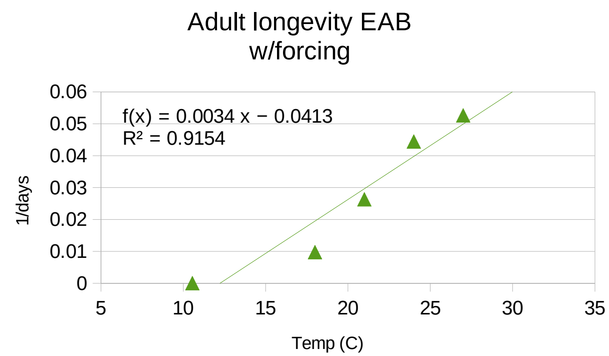
Reported Tlow and DDC req. (females)

	Tlow (degC)	DD req.	est days at 25C	Rough Est DD req. (Tlow=12.2)
Prepupae (J-larva)	11.5	121	9.0	115
Pupae	14.7	115	11.1	142
Teneral adult	10.1	64	4.3	55
Egg	13.9	155	14.0	179
J-larva to adult	13.5	345	30.0	384

Longevity (females)

Temp C	Days	Tlow	DDC	1/days
10.55	20000			0.00005
18	102.5	12.2	595	0.009756098
21	38	12.2	334	0.026315789
24	22.5	12.2	266	0.044444444
27	19	12.2	281	0.052631579
33	5	12.2	104	
35	0	12.2	0	

	no forcing	w/forcing
slope	0.0049	0.0034



intercept	-0.0768	-0.0413
R-sq	0.9781	0.9154
Tlow (-a/b)	15.70	12.22
DD req. (1/slope)	204	296

A6. Petrice, T. R., L. S. Bauer, D. L. Miller, T. M. Poland, and F. W. Ravlin. 2020. A phenology model for simulating *Oobius agrili* (Hymenoptera: Encyrtidae) seasonal voltinism and synchrony with emerald ash borer oviposition. Environmental Entomology. doi: 10.1093/ee/nvaa169

- Developed a multiple cohort summation model to simulate egg parasitoid (Oobius agrili) generations
- Goal was to test for synchrony in host-parasitoid interactions along a north-south gradient in U.S.
- Validated model using trapping data from four field sites sampled over a 3-yr period in Michigan
- EAB adult female emergence rates were measured by rearing diapausing J-larvae from white and green ash logs (from several sites in Midwest)
- J-larvae were collected in January at multiple sites in IN and MI
- Logs were stored at 4C for a maximum of 120 days before transferring to a temperature treatment
- Logs held at 10 and 15C were transferred to 25C (adults died before emerging at the 15C treatment), so rates for 0 and 10C were calculated (not empirical)
- The number of days from female adult emergence to their last day of laying fertile eggs was measured
- The number of eggs per female and number of females that laid eggs peaked at 30C and then declined (both were 0 at 39.1C)

Analysis of data presented in Table 1

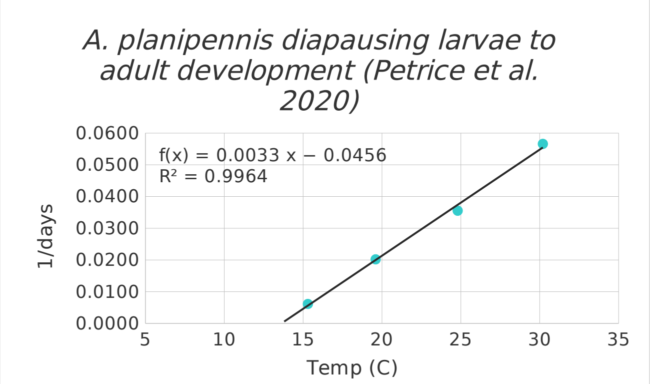
- Data points at 34 and 39C not used because temperature - development relationship becomes nonlinear

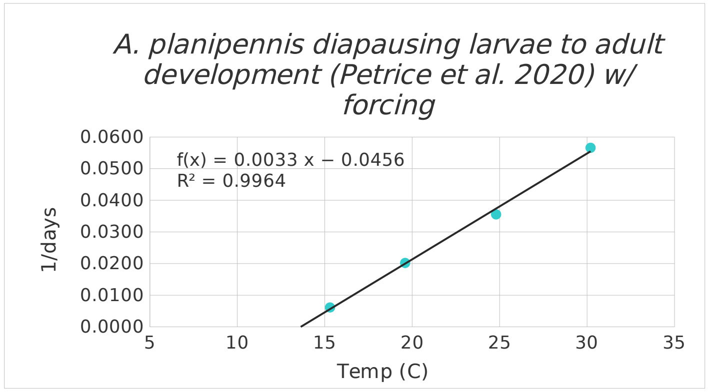
Diapausing J-larvae (females) to emerged adults (no forcing)

Temp C	1/days
15.3	0.0061
19.6	0.0202
24.8	0.0355
30.2	0.0566
34	
39	
slope	0.0033
intercept	-0.0456
R-sq	0.9964
Tlow (-a/b)	13.6
DD req. (1/slope)	299

Diapausing J-larvae (females) to emerged adults (with forcing)

Temp C	1/days	Days
12.22	0.0043	232.56
15.3	0.0061	163.13
19.6	0.0202	49.50
24.8	0.0355	28.15
30.2	0.0566	17.67
34		
39		
slope	0.0030	
intercept	-0.0366	
R-sq	0.9771	
Tlow (-a/b)	12.22	
DD req. (1/slope)	334	





Analysis of data presented in Table 2

Oviposition longevity rate (males/females put together w/in 1 day of emergence)

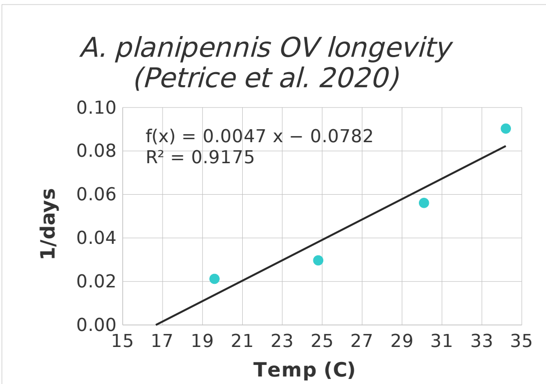
NOTE: the number of eggs over time was not quantified, so cannot quantify when OV actually began

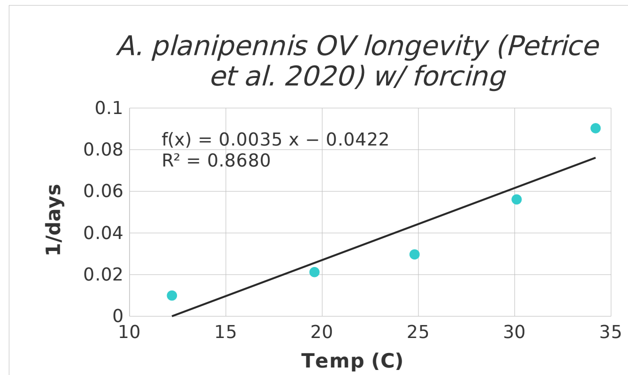
PreOV to last OV

Temp C	1/days	Days
19.6	0.0212	47.17
24.8	0.0297	33.67
30.1	0.0561	17.83
34	0.0903	11.07
slope	0.0047	
intercept	-0.0782	
R-sq	-0.0782	
Tlow (-a/b)	16.7	
DD req. (1/slope)	213	

PreOV to last OV (w/ forcing) (OK to use for adult longevity)

Temp C	1/days	Days
12.2	0.00995	
19.6	0.0212	47.17
24.8	0.0297	33.67
30.1	0.0561	17.83
34	0.0903	11.07
slope	0.0035	
intercept	-0.0422	
R-sq	0.8680	
Tlow (-a/b)	12.20	
DD req. (1/slope)	289	





From Table 5 Model predictions of events vs. observed

				First adults in trap		1^{st} adult emerg. DD12.2C 226DD Predicted		Peak trap capture ca same		95% adult emerg. DD12.2C 623DD Predicted	
uspest.org weather s	Location	Loc. Lat/Long	year	Obs. Date	DD12.2C	Date	Diff Days	As 95% emerg	DD12.2	Date	Diff Days
D3512	Eastport MI	45.11/-85.33	2016	06-23-2016	244	06-20-2016	3	08-04-2016	581	08-10-2016	-6
KAMN	Gratiot-Saginow MI	43.23/-84.45	2016	06-21-2016	280	06-15-2016	6	07-18-2016	527	07-26-2016	-8
C9742	Harris Nature C. Ok	42.69/-84.37	2016	07-04-2016		06-04-2016	30	08-01-2016	801	07-18-2016	14
C9742	Legg Park MI	42.69/-84.38	2016	06-08-2016	249	06-04-2016	4	08-01-2016	801	07-18-2016	14
	Eastport MI		2017	NA		06-17-2017		NA		08-20-2017	
KAMN	Gratiot-Saginow MI		2017	06-15-2017	277	06-11-2017	4	08-03-2017	682	07-28-2017	6
C9742	Harris Nature C. Okemos, MI		2017	06-15-2017	326	06-07-2017	8	08-03-2017	792	07-18-2017	6
C9742	Legg Park MI		2017	06-15-2017	326	06-07-2017	8	07-05-2017	496	07-18-2017	-13
	Eastport MI		2018	NA		06-13-2018		NA		07-30-2018	
KAMN	Gratiot-Saginow MI		2018	06-14-2018	255	06-09-2018	5	07-19-2018	599	07-22-2018	-3
C9742	Harris Nature C. Okemos, MI		2018	06-21-2018	402	05-31-2018	21	07-19-2018	715	07-12-2018	7
C9742	Legg Park MI		2018	06-14-2018	327	05-31-2018	14	07-05-2018	563	07-12-2018	-7
				AVG:	298		10.3		655.7		1

Results: This study predicted events ca. 3-30 days (avg 10 days) later than the 12.2C model based on Duarte's data

A7. Wang, X-Y, Z-Q Yang, J. R. Gould, Y-N Zhang, G-J Liu, and E-S Liu. 2010. The biology and ecology of the emerald ash borer, *Agrilus planipennis*, in China. Journal of Insect Sciences 10:128. insectscience.org/10.128

- Conducted field and lab studies of populations in Tianjin, China (most individuals were univoltine)
- Part of their study involved raising individuals in the lab at "room temperature" (18 to 22C), depending on the life stage
- Longevity reported below is days in pupal cells (after eclosion) plus longevity after exiting log (no signif. diff between males and females)
- Estimates of longevity are consistent with estimates by Lyons and Jones 2005
- First pupa and adult data in Table 3 don't seem to be usable

Used a Tlow of 12.2C to caculate DDs

Stage	Days	Avg. temp C	Tlow	DDC	DDF
Egg	15.1	22.9	12.20	162	291
Pupa	20	19	12.20	136	245
Longevity (inc. in pupal cell)	30.4	24	12.20	359	646
Longevity (after emergence)	21.7	24	12.20	256	461

A8. Synthesis of lab-based results

Thresholds

Source	Country	Latitude (N)	Egg	Egg-to-J-larvae	J-larvae to pupae	Pupae	Pre-OV to OV	J-larva to adult emerg.
Duan et al. 2013	Ohio, USA	40.5	13.8	8.6				
Lyons & Jones 2005	Ontario, CA	42.2	13.9		11.5	14.7	10.1	13.5
Petrice et al. 2020	IN & MI, USA	42.0						13.6
		Avg.						

Stage durations (12.2C lower threshold)

Source	Country	Latitude (N)	Egg	Egg hatch-to-J-larvae	J-larvae to pupae	Pupae	Pre-OV to OV	Adult longevity	Egg-to-adult	J-larva to adult emerg.
Duan et al. 2013	Ohio, USA	40.5	174	488						
Lyons et al. 2004	Ontario, CA	42.2					261	313		
Lyons & Jones 2005	Ontario, CA	42.2	179		115	142		296		384
Petrice et al. 2020	IN & MI, USA	42.0						289		334
Wang et al. 2010	Tianjin, China	39.1	162			136		256		
		Avg.	171	488	115	139	261	288		359
							Our model using 72 DD12.2 for Pre-OV, not this much higher value			^should more or less co Dds to 1st adult emerge

Site Model (EAB2) based on above analysis and DDRP cohort analysis

DDC12.2	DDF54	label	notes	cohort	OL	P	Adult Emergence = OL+P	PreOV	Adult to 50% OV		Egg Hatch = OL+P+Pre	A	E
226	407	first adult eme	round down fro	1	96	135	231	72	145	first egg hatc	475	145	172
269	484	10% adult emergence		2	134	135	269	72	145		513	145	172
				3	173	135	308	72	145		552	145	172
365	657	50% adult emergence		4	211	135	346	72	145	50% egg hatc	663	145	172
				5	250	135	385	72	145		629	145	172
				6	288	135	423	72	145		667	145	172
				7	327	135	462	72	145	ca. end adult	864	145	172
475	855	first egg hatch								"=ca. end of last cohort ol+p+preov+adult			
680	1224	50% egg hatch	(combined events 663 for 50% egg hatch, 706 for ca. 95% adult emerg.)										
864	1555	approx end of adult activity	(assuming only OW Jlarvae emerge)										
1139	2050	approx end of adult activity	(assuming some OW larvae reached Jlarvae early enough in spring to emerge in same year; based on Duarte 2013)										

notes: the 50% adult emergence should take the midpoint of cohort 4 which would be avg of adult emerg for cohort 4 and 5 = 365 DDC12.2

end of adult activity would be last cohort

B) Analysis of field-collected data

B1. Abell, K. J., J. J. Duan, and P. M. Shrewsbury. 2019. Determining optimal parasitoid release timing for the biological control of emerald ash borer (Coleoptera: Buprestidae). Florida Entomologist 102:691–694.

- Studied the timing of optimal biocontrol release for EAB at 2 sites in central Maryland in 2017:
    1. US National Arboretum, Washington DC (38.90627N, 76.97324W)
    2. Montgomery Co., Maryland (39.15586N, 77.15482W)
- Figures are shown below and dates and DDs (est. by authors using Tlow = 10C) for key events are summarized in below table
- Dates are not useful because they only sampled twice (2 to 9 Aug, and 26 - 31 Oct) - the first occurrence of events were probably missed

				KGAI Montgom Co		
Event	Date	DDs (F)	DDs (10C)	DDs (54F)	DDs (12.2C)	
First emergence	5/18/2017	862	479	486	270	This value may not be reliable b/c they didn't sample before this date
Peak adult activity	6/15/2017	1481	823	880	489	
Adults absent	7/13/2017	2342	1301	1514	841	
All larval instars present	early Aug	3056	1698	2018	1121	
J-larvae dominant	late Oct	4878	2710	3200	1778	

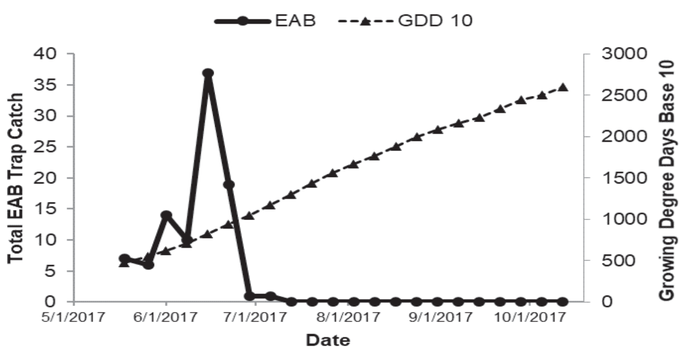


Fig. 1. Number of emerald ash borer adults captured in green funnel traps (pooled across sites for each sample date) in central Maryland and Washington, DC, in 2017. The secondary Y-axis is growing degree d base 10 °C (GDD10) obtained from Ronald Reagan National Airport weather station in Washington, DC, USA.

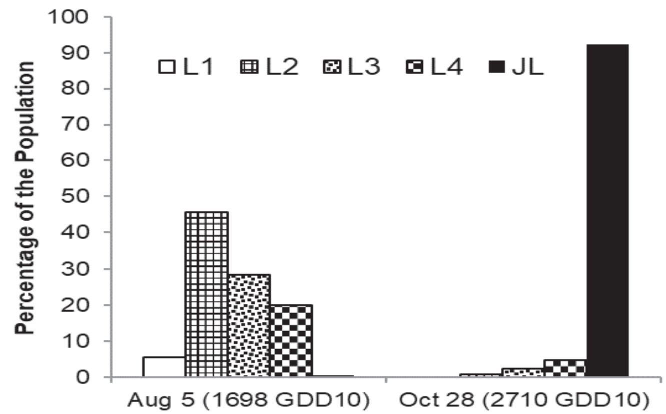


Fig. 2. Percentage of each immature stage of emerald ash borer at the approximate mid- and endpoint of the season collected in central Maryland and Washington, DC, in 2017. Growing degree d base 10 °C (GDD10) shown in parentheses for each date were obtained from Ronald Reagan National Airport weather station in Washington, DC, USA. L1 = first instar, L2 = second instar, L3 = third instar, L4 = fourth instar, and JL = J-larva.

B2. Bohannon, G. R., C. L. Johnson, R. M. Jetton, and K. L. F. Oten. Phenology and voltinism of emerald ash borer (Coleoptera: Buprestidae) in Central North Carolina. Environmental Entomology. 51:1077-1085.

- Studied phenology of EAB in central North Carolina to inform biological control efforts
- Monitored EAB in green ash stands over 26 consecutive months (Jun 2019 to Aug 2021)
- Populations were univoltine
- Third and fourth instars in galleries occurred mostly between 1100-1900 DDC10
- Relevant data reported below

First observations of live J-larvae	DDs (base 10C)	Station E1728 Garner NC Dds (base 12.2)

8/23/2019	2331	1955		
10/13/2020	2824	2322		
8/2/2021	1753	1444	Beginning of larvae to J-larvae	
	2303		1403	

B3. Duarte, S. 2013. Characterizing prepupal diapause and adult emergence phenology of emerald ash borer. The Ohio State University, Columbus, OH.

- Note: First adult emergence changed from 599 to 550 DDF to match earlier models and because of high error rates and low sample size. 550 is in line w/ calculations in Source B2 (407-593 DDF)

Summarized from Tables 3.2 and 3.7-3.13 (using 50F Tlow, DDF); revised below

		1st emerge		10% emerge		50% emerge		peak emerg (95%)		end of emerge	
	Latitude (N)	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
Cincinnati OH	39º8'	601	477	666	693	973.8	905.4	1568	1885	2714	2855
Columbus OH	40º1'		657				747		1447		2255
Delaware OH	40º21'	630		644.4	696.6	829.8	1011.6	1490	2408	2273	3334
Wooster OH	40º47'	614		724.5	633.6	823.5	756	1085	1069	2156	2752
Toledo OH	41º39'	524	517	525.6	580.5	887.4	867.6	1640	1328	2718	2693
Midland MI	43º37'	670	661		721.26	721.26	892.8	924	1703	1663	2286
mean		607.8	578.0	640.1	665.0	847.2	863.4	1341.4	1640.0	2304.8	2695.8
st dev		53.5	95.0	83.5	57.2	92.7	99.7	317.2	472.1	439.7	399.5
C.V		8.8	16.4	13.0	8.6	10.9	11.5	23.6	28.8	19.1	14.8
Mean 2011-2012		**592.9**		**652.6**		**855.3**		**1490.7**		**2500.3**	

Summary of results

Event	DDF	DDC
First adult emergence in spring	550	306
10% adult emergence	653	363
50% adult emergence	855	475
95% adult emergence	1491	828
Last adult emergence	2500	1389

96	35.5555556
97	36.1111111
100	37.7777778

Table 3.2 Dates for first emergence, peak of emergence (95%), end of emergence, cumulative degree days using 10°C and 50°F number of beetles emerged and length of emergence of emerald ash borer (*Agrilus planipennis* Fairmaire).

Site	Coordinates	Year	First Emergence Date	First Emergence DD 10°C	First Emergence DD 50°F	Peak of Emergence Date	Peak of Emergence DD 10°C	Peak of Emergence DD 50°F	End of Emergence Date	End of Emergence DD 10°C	End of Emergence DD 50°F	Adults observed	Length of emergence (days)
Cincinnati, OH	39°8'0"N, 84°21'29"W	2011	20-May	334	601	27-Jun	871	1568	8-Aug	1508	2714	80	80
		2012	25-Apr	265	477	5-Jul	1047	1885	6-Aug	1586	2855	567	103
Columbus, OH	40°0'41"N, 83°2'11"W	2011	--	--	--	--	--	--	--	--	--	--	--
		2012	10-May	365	657	18-Jun	804	1447	15-Jul	1253	2255	223	66
Delaware, OH	40°21'15"N, 83°3'52"W	2011	2-Jun	350	630	11-Jul	828	1490	9-Aug	1263	2273	32	70
		2012	25-Apr	182	328	27-Jul	1338	2408	10-Sep	1852	3334	323	138
Wooster, OH	40°46'45"N, 81°56'14"W	2011	1-Jun	341	614	26-Jun	603	1085	7-Aug	1198	2156	619	76
		2012	18-May	352	634	22-Jun	594	1069	26-Aug	1529	2752	1221	100
Toledo, OH	41°39'25"N, 83°33'9"W	2011	30-May	291	524	11-Jul	911	1640	15-Aug	1510	2718	472	77
		2012	12-May	287	517	22-Jun	738	1328	11-Aug	1496	2693	505	91

50.00% emerge

	DOY	DATE
2011	157	Jun-6-11
2012	144	May-23-12
2011		
2012	138	May-17-12
2011	159	Jun-8-11
2012	163	Jun-11-12
2011	162	Jun-11-11
2012	148	May-27-12
2011	164	Jun-13-11
2012	153	Jun-1-12

Midland, MI	43°37'28"N, 84°14'49"W	2011	17-Jun	372	670	1-Jul	519	934	29-Jul	924	1663	21	44	2011	
		2012	31-May	367	661	17-Jul	946	1703	10-Aug	1270	2286	120	71	2012	167 Jun-15-12

Summarized from Tables 3.2 and 3.7-3.13 (using 54F Tlow, 97 Tupper, DDF, single sine method)

			1st emerge		10% emerge		50% emerge		peak emerg		end of emerge	
Weather Station		Latitude (N)	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
KLUK	Cincinnati OH	39º8'	431	327			733	657	1120	1505	2214	2309
KOSU	Columbus OH	40º1'		396						965		
D2111, OH104	Delaware OH	40º21'	468	301			604	780	1220	1383	1913	2461
KBJJ, OH089	Wooster OH	40º47'	431	360			601	498	808	876	1699	2020
AR605, OH135	Toledo OH	41º39'		370			518	655	1074	1034	1909	2204
KMBS	Midland MI	43º37'		472				653		1370		1823
	mean		443.3	371.0	#DIV/0!	#DIV/0!	614.0	648.6	1055.5	1188.8	1933.8	2163.4
	st dev		21.4	59.6	#DIV/0!	#DIV/0!	88.8	100.1	175.9	261.7	211.9	248.9
	C.V		4.8	16.1	#DIV/0!	#DIV/0!	14.5	15.4	16.7	22.0	11.0	11.5
	Mean 2011-2012		**407**		**#DIV/0!**		**631**		**1122**		**2049**	

Summary of results

	Tlow=54F/12.2C		
Event	DDF	DDC	
First adult emergence in spring	407	226	
10% adult emergence	482	268	← temp. guess based on the 50/10 model above
50% adult emergence	631	351	
95% adult emergence	1122	623	
Last adult emergence	2049	1138	

B4. Duan, J. Unpublished trapping data set provided to B. Barker on March 26, 2021.

- Jian Duan provided data on adult emergence from several urban plots near the USDA ARS Beneficial Insects Introduction Research Unit in Newark, DE
- Data were collected on a weekly basis on trunks and main branches (ground to 2 m)
- From these data, determined the earliest date (first) emergence, peak emergence, and last date of emergence
- A few outliers were ignored for last date of emergence
- Calcuated DDs using USPest.org DD calculator (simple avg., base 10C, Tupper = 30C; also Single Sine, 12.2, 40), start date = Jan 1

added revised 54F/12.2C thresholds in yellow

Weather station for DD calculations		Stations all near Newark, DE										
		DE039		DE039		DEL10		DE004		E9357		
		Tlow = 50F/10C		Tlow = 54F/12.2C		Tlow = 54F/12.2C		Tlow = 54F/12.2C		Tlow = 54F/12.2C		
Event	Date	DDF	DDC	DDF	DDC	DDF	DDC	DDF	DDC	DDF	DDC	Notes
First adult emergenc	5/25/2020	394	219	238	132	307	171	287	159	268	149	First evidence of exit hc
Peak emergence	6/4/2020	574	319	382	212	469	261	444	247	427	237	Peak of 44 individuals a
End emergence	7/16/2020	1559	866	1197	665	1364	758	1330	739	1302	723	Virtually no emergence

Results: Distribution of emergence time DDs are considerably earlier than Duarte 2013 (Source B2).

B5. Nalepa, C. A., K. L. F. Oten, and M. A. Bertone. 2021. Overwintering developmental stages of emerald ash borer in North Carolina. Florida Entomologist. 104:213-217.

- Collected 4 yrs (2017-2020) of data on OW stages in Granville Co., NC, near where it was first detected in 2013
- In 2017 collected data at 2 sites (north of Stovall, and in Butner) but subsequent years only Butner was studied because of ash death at Stovall
- Trees were felled at EAB studied under scope
- In 2017, 85% of larvae had developed to pupal stage by 252 DDCs

Table 1. Developmental stages of OW EAB during winter in Granville Co. DDs calculated using EAB (Duarte 2013) model at USPest.org

add new threshold-based estimates in yellow

		Tlow = 50F/10C		Tlow = 54F/12.2C				
Year	Date	DDF	DDC	DDF	DDC	% larvae	% J-larvae	% pupae
2017	28-Feb	454	252					84.7
2018	9-Feb	141	78			95.2	4.8	0.0
2019	5-Feb	140	78			92.3	7.7	0.0
2020	4-Feb	237	132			46.7	53.3	0.0

B6. Petrice, T. Unpublished trapping data set provided to B. Barker on March 26, 2021.

- Toby Petrice provided adult trapping data (counts of males and females) from 2019 from three locations in south-central Michigan
- From these data could infer first emergence (first catch), peak activity (highest catch), and end of activity (no catch)
- Calcuated DDs using USPest.org DD calculator (simple avg., base 10C, Tupper = 30C), start date = Jan 1

Site	Lat	Long	Weather station for DD calculations
gsw	43.2337	-84.4477	MIITH MAWN Ithaca MI (lat 43.315, long -84.488)[5.96 miles away]
lpc	42.69403	-84.3822	MIHTC MAWN Mshuhtrc MI (lat 42.711, long -84.4758)[5.1 miles away]
lpr	42.6965	-84.3752	MIHTC MAWN Mshuhtrc MI (lat 42.711, long -84.4758)[5.23 miles away]

								USPEST.ORG			
Site	Event	Date	DOY	DDF50	DDC10	Notes	Sta. Used	DDC12.2	Date	Days Diff	
gsw	First detection	6/23/2019	174	508	282		C2125	231	06/23/19	0	
lpc	First detection	6/25/2019	176	597	331		E9296	246	06/23/19	2	
lpr	First detection	7/2/2019	183	774	430		E9296	328	06/23/19	9	
gsw	Peak activity	7/16/2019	197	1040	578			475			
lpc	Peak activity	7/9/2019	190	928	516			399			
lpr	Peak activity	7/2/2019	183	774	430	Went from 0 to peak abundanc		328			
gsw	End activity	7/31/2019	212	1384	769			639	07/30/19	1	Using 95% adult emerg
lpc	End activity	8/6/2019	218	1550	861			677	07/31/19	6	
lpr	End activity	8/1/2019	213	1448	805			631	07/31/19	1	

	DDF50	DDC10	DDC12.2
Avg. first detection	626	348	268
Avg. peak activity	914	508	401
Avg. end activity	1461	812	649
Adult DD (first detection to peak activity)	288	160	132

Results: Distribution of emergence time DDs are concordant with other studies in SE Michigan (see Source B9),
Results are almost identical to current model for first emergence and end activity vs 95% adult emergence (model derived from Duarte data)

B7. Gould, J. R., M. L. Warden, B. H. Slager, and T. C. Murphy. 2020. Host overwintering phenology and climate change influence the establishment of *Tetrastichus planipennisi* Yang (Hymentoptera: Eulophidae), a larval parasitoid introduced for biocontrol of the emerald ash borer. Journal of Economic Entomology 113:2641-2649.

- Monitored OW stages of EAB at 90 sites in 22 states, and produced model of percentage of insects overwintering as J-larvae
- Linked model to establishment success of the biocontrol parasitoid, and projected it to future climates

- Results: accumulated growing DDs (GDD) strong predictor of prop. of EAB that overintered as J-larvae vs. more immature larval stages (see figs)

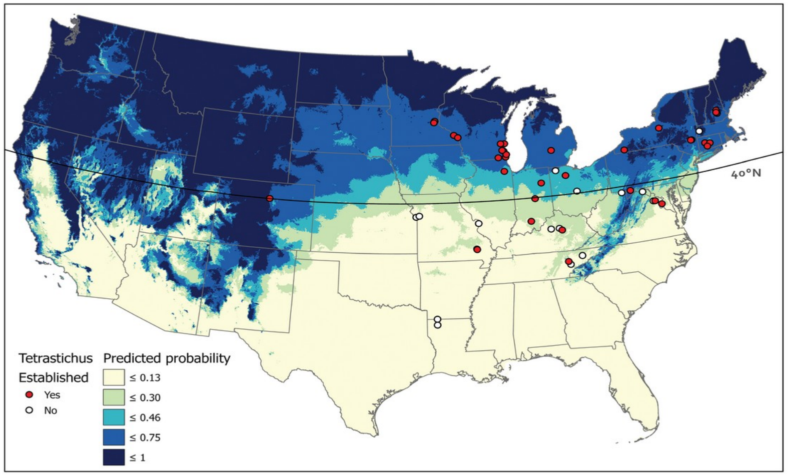


Fig. 2. Predicted proportion of emerald ash borer that spend the winter as larvae instar 1–4, not as J-larvae. Locations where *T. planipennisi* has been collected 2 or more years following the final release are indicated by shaded dots. Locations where samples were collected but *T. planipennisi* was not recovered are marked in white.

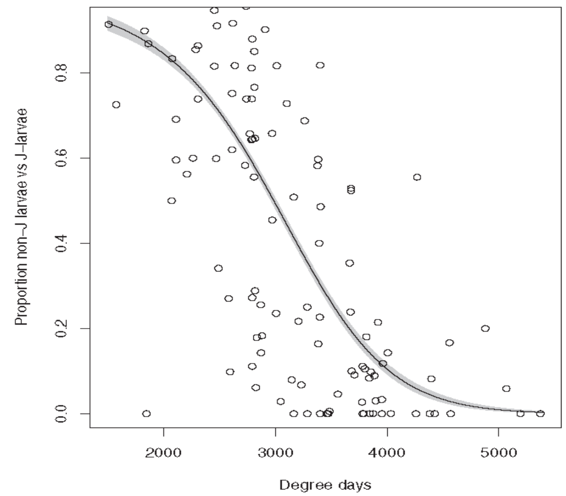


Fig. 1. Proportion of emerald ash borer that overwinter as larvae (instar 1–4) versus J-larvae plotted against the number of GDD (base 50°F). The shaded area around the solid regression line represents the 95% CI.

B8. Jones, M. I., J. R. Gould, H. J. Mahon, M. K. Fierke, and B. Sullivan. 2020. Phenology of emerald ash borer (Coleoptera: Buprestidae) and its introduced larval parasitoids in the Northeastern United States. Journal of Economic Entomology 113:622–632.

- Studied phenology of EAB and parasitoids at 2 sites and an open-air insectary from 2015 to 2017 in Syracuse, NY
- EAB overwinters in NY as larvae in galleries and J-larvae (prepupae) in pupal cells in the wood (below table)
- Part of population has 1-yr life cycle, other a 2-yr life cycle (sampling suggested <25% overwintered as larvae; rest were prepupae = J-larvae)
- They detected actively feeding 3rd/4th instars in early May to late-October, w/ peak in numbers in Summer and Fall (Fig. 2)
- First peak was June to late July (~500 to 1000 DD10F) and were larvae from the 2-yr life cycle
- EAB from 1-yr life cycle:
  - Pupae detected in early May
  - Pharate adults detected in early June
    (pharate means that metamorphosis is complete but adult waits until the time is right to emerge)
  - Females oviposited in late August (~1200 DD10F)
  - Pupae or pharate adults not detected after mid-July
  - Most larvae were 4th instar and were excavating pupal cells for J-larval devel by mid-Oct

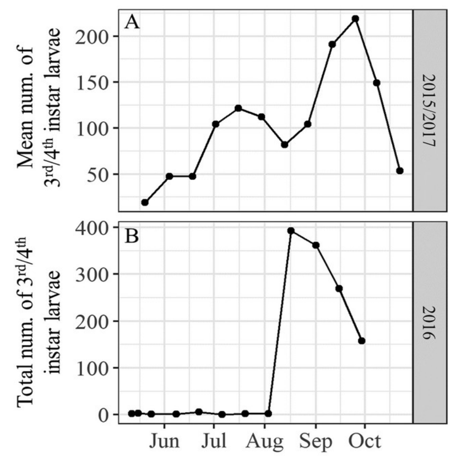


Fig. 2. Actively feeding third/fourth instar EAB larvae were detected from May to October in Syracuse, New York. A) Mean number of larvae collected in 2015/2017 and B) total number of EAB collected in 2016 following a freeze event in February that resulted in high overwintering mortality. The first peak starting in June (~500 DD_{10}) is EAB oviposited the previous summer and the second peak starting in late August (~1,200 DD_{10}) is EAB oviposited by the current year's emerging females.

Number of EAB, summarized by month and life stage, recovered from 112 trees
felled and sampled from late spring to early fall in 2015, 2016, and 2017

Stage	May	June	July	August	Sept	Oct
1st/2nd instar	45	59	991	1550	112	51
3rd/4th instar	111	284	778	768	1464	400
Prepupae	8	1	57	41	36	1129
J-larvae	174	18	0	0	0	0
Pharate adult	0	31	6	0	0	0

Reported DDs (base 10C) from publication

Event	Date	DDF	DDC

Peak larval dev.	late August	2160	1200	1-yr life cycle (univoltine)
Peak larval dev.	June	900	500	2-yr life cycle (semivoltine)
J-larva devel.	15-Oct			
Adult emerg.	14-Jun	765	425	reported DDs for 2016 and 2017

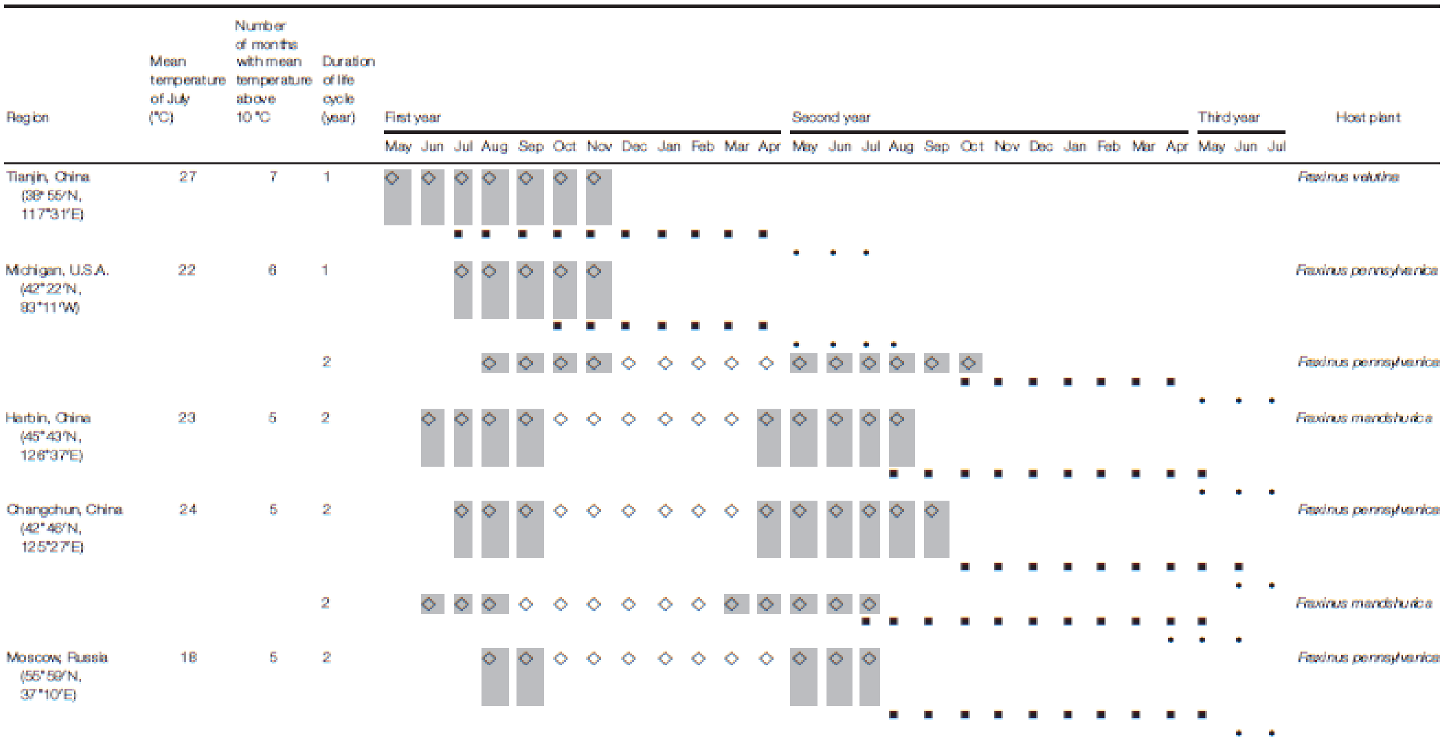
Fig. 2. Actively feeding third/fourth instar EAB larvae were detected from May to October in Syracuse, New York. A) Mean number of larvae collected in 2015/2017 and B) total number of EAB collected in 2016 following a freeze event in February that resulted in high overwintering mortality. The first peak starting in June (~500 DD_{10}) is EAB oviposited the previous summer and the second peak starting in late August (~1,200 DD_{10}) is EAB oviposited by the current year's emerging females.

Note: adult emergence DDs seem a bit high; perhaps they did not observe first emergence. Could be used for forecast validation though.

B9. Orlova-Bienkowskaja, M. J., and A. O. Bienkowski. 2016. The life cycle of the emerald ash borer *Agrilus planipennis* in European Russia and comparisons with its life cycle in Asia and North America. Agricultural and Forest Entomology. 18:182-188.

- Studied the timing of life stages in European Russia and compared results to those in other regions of world
- Development of most specimens in the Moscow region was 2 years (study conducted in 2013 and 2014)
- Adult flight started in early June in Moscow - adults captured from June 8 to July 5 in 2013, and from June 2 to July 9 in 2014

Table 2 Life cycle of *Agrilus planipennis* in different parts of its range: China (Wang *et al.*, 2005; Liu *et al.*, 2007; Wei *et al.*, 2007), U.S.A (Cappaert *et al.*, 2005) and European Russia (original data)



◇, larvae; ■, prepupae; •, adults. The period of active feeding of larvae is shaded grey. Egg and pupa stages are not shown. The duration of life cycle was determined based on the seasonal presence of different life stages inside trees. Climatic data are from Hijmans *et al.* (2005).

B10. Palmer, J. F. 2018. Biological control of emerald ash borer in the southern US: seasonality, phenological synchrony, and implications for management. Master's Thesis, University of Tennessee, Knoxville.

- The study focused primarily on parasitoids of EAB, but also presented phenological results for EAB (see figures below)
- Study sites were Doyle Farm (near Powell, Knox Co.) and Oak Ridge National Laboratory (Anderson Co.) in Tennessee
- The "boring" stage below refers to 4th instar larave that have begun to bore deeper into the tree to overwinter

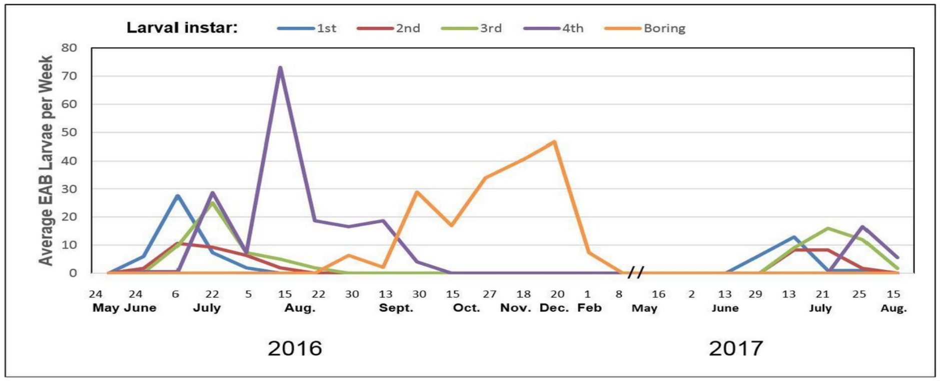


Figure 3.13. Combined phenological data of emerald ash borer at Doyle Farm, 2016 and 2017.

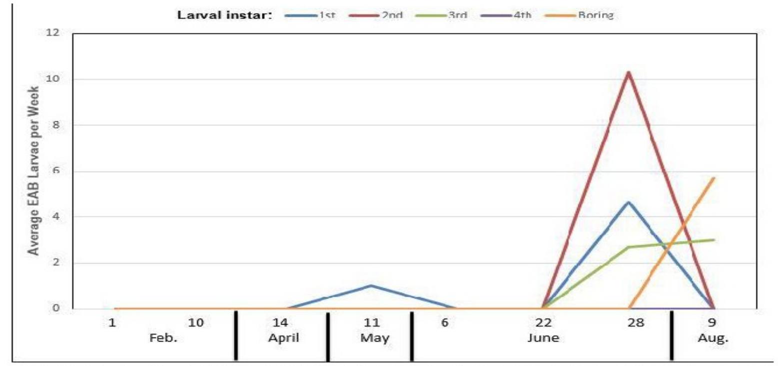


Figure 3.12. Phenology of emerald ash borer at Oak Ridge National Laboratory, 2017.

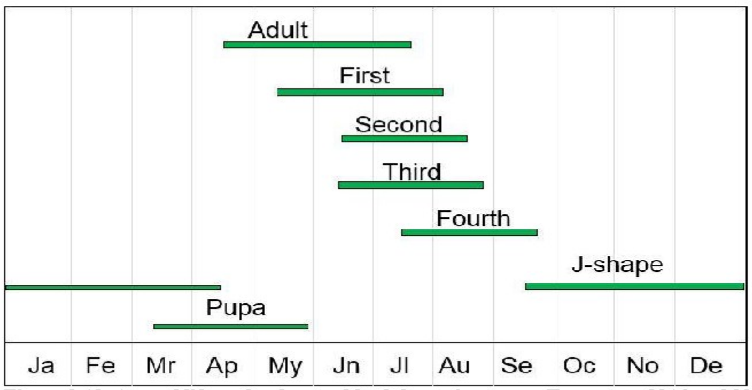


Figure 3.10. Annual life cycle of emerald ash borer in eastern Tennessee, 2016 and 2017.

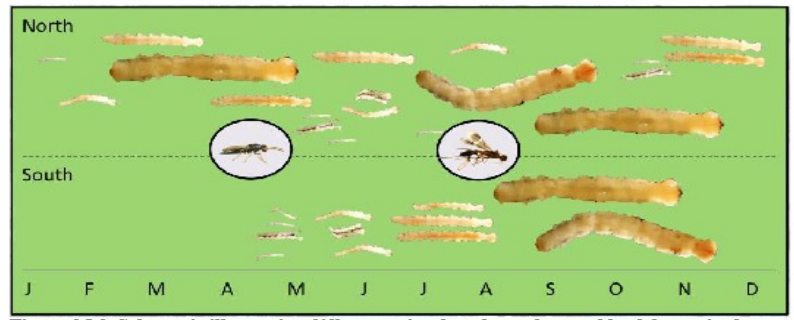


Figure 3.16. Schematic illustrating differences in phenology of emerald ash borer in the northern and southern United States, as well as anticipated emergence times of adult parasitoids.

Analysis based on Palmer's data

- Calcuated DDs using USPest.org DD calculator (simple avg., base 10C, Tupper = 30C), start date = Jan 1
- Weather station for both sites: Oak Ridge National Lab: KOQT Oak Ridge TN

Event	Site	Year	Date	DDC10	larva to j-larva	DDC12.2
Beginning J-larva development	Oak Ridge	2017	28-Jul	1585	529	1346
Beginning J-larva development	Doyle Farm	2016	22-Aug	1923	998	1750
Beginning larva development	Doyle Farm	2016	1-Jun			
Beginning larva development	Doyle Farm	2017	13-Jun	925		
Beginning larva development	Oak Ridge	2017	22-Jun	1056		
End larval devel. (adults all emerged)	Doyle Farm	2017	8-Apr	235		
Peak larval development	Doyle Farm	2017	23-Jul	1509		
Peak larval development	Oak Ridge	2017	28-Jul	1585		
Peak larval development	Doyle Farm	2016	15-Aug	1820		

Event	Average DDC
Beginning J-larva development	1754

Beginning larva development	991
Peak larval development	1638
Beg. larva to beginning of J-larva	764

B11. Pellecchia, S. 2020. Emerald ash borer development across a latitudinal gradient: Implications for biocontrol. Master's Thesis, University of Kentucky, Lexington, KY.

- Studied variation in development at sites in KY (38N) and GA (34N)
- Sampling was at 1 site each in Anderson, Fayette, Jessamine and Spencer counties in KY; and sites in Cobb county in GA
- The longitudinal coordinates for the sites were not reported for this aspect of study
- EAB galleries were inspected from sites in KY (2019 N = 100, 2020 N = 99) and GA (2019 N = 24, 2020 N = 52)
- No significant differences in life stages present in KY and GA, but sig diffs found between KY/MI and GA/MI in 2019 and 2020
- Adults are represented by the presence of exit holes
- NOTE: adult emergence DOY are outliers - perhaps exit holes were from the previous year? Will not use adult data.
- NOTE: they did not determine whether immature stages were from univoltine or semivoltine insects, so data not that useful

Tree fell date	Latitude	DOY	Approx. coordinates
03/12/19	38N (KY)	70	38.13N, -84.97W (Stand 1, Plot 1, Anderson Co.; Appendix A)
02/11/20	38N (KY)	41	38.13N, -84.97W (Stand 1, Plot 1, Anderson Co.; Appendix A)
04/10/19	34N (GA)	99	34N, -85W
2/21/2020	34N (GA)	51	34N, -85W

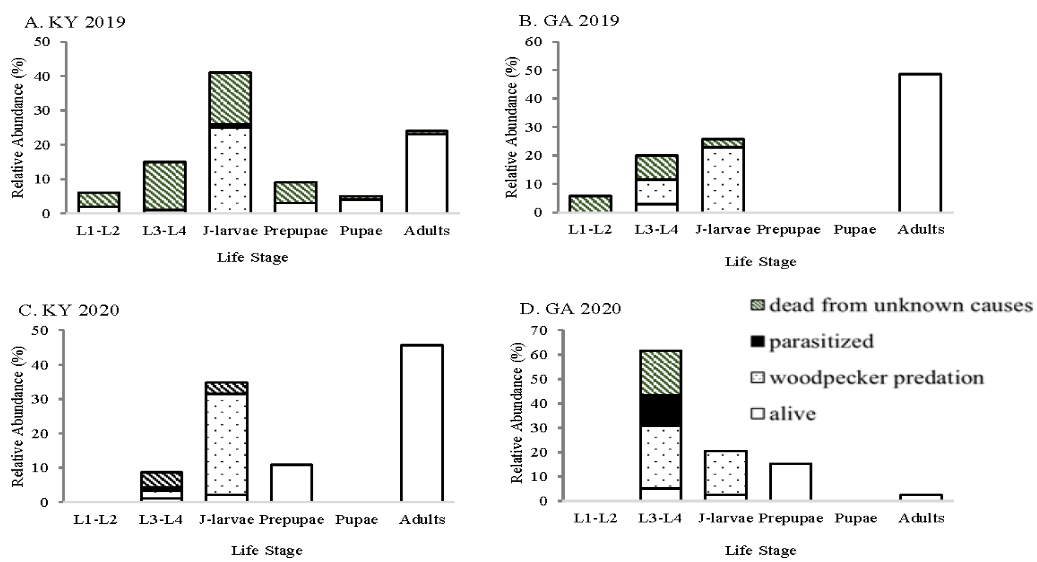


Fig. 2.2. Relative abundance of EAB life stages and mortality factors identified on felled trees
Precise dates of the sampling are in the above table.

B12. All field data including data reported in publications, abstracts, and general reports not listed above

- Growing degree days use base 50F (10C)

Confusion if some authors reported wrong DD units!!

1. First adult emergence

Event	Area	Latitude	Year	Dates	DDF low	DDF high	DDF	DDC	Reference
					using 50F and 10C as thresholds				

First adult emerg.*	Essex Co. ON	42.2	2003	28-May			290	161	Lyons & Jones 2005
First adult emerg.	Ann Arbor MI	42.3	2003	6/5 - 6/13	471	584		262	Brown-Rytlewski & Wilson 2005
First adult emerg.	Novi MI	42.5	2004	5/11 - 5/18	348	463	406	225	Brown-Rytleski & Wilson 2005
First adult emerg.	Troy MI	42.6	2004	5/25 - 6/1	444	518	481	267	Brown-Rytleski & Wilson 2005
First adult emerg.	Detroit MI	42.3	2003	13-Jun					Rogriguez-Saona et al. 2007
First adult emerg.	Knoxville TN	36	2016-2017	average			500	278	Palmer 2018
First adult emerg.	OH and MI	see above	2011-2012	average			550	306	Duarte 2013
First adult emerg.	Newark, DE	39.7	2020	25-May			394	219	Duan 2021
First adult emerg.	Randolph, NY	42.2	2010	10-Jun			539	299	Fierke et al. 2013
First adult emerg.	SouthCen. MI	see above	2019	average			626	348	Petrice 2021 (higher than others!)

*synthetic - PRISM data converted to DD using uspest.org; file=SOUTHGATEMI03.txt

2. 50% adult emergence

Event	Area	Latitude	Year	Dates	DDF low	DDF high	DDF	DDC	Reference
50% adult emerg.	OH and MI	see above	2011-2012	average			855	475	Duarte 2013
50% adult emerg.*	Essex Co. ON	42.2	2003	25-Jun			702	390	Lyons & Jones 2005
50% adult emerg.*	Essex Co. ON	42.2	2004	24-Jun			914	508	Lyons & Jones 2005

3. Peak adult emergence

Event	Area	Year	Dates	DDF low	DDF high	DDF	DDC	Reference
Peak adult emerg.	Ann Arbor MI	2003	6/13 - 6/19	584	705	645	358	Brown-Rytlewski & Wilson 2005
Peak adult emerg.	Novi MI	2004	6/1 - 6/8	572	759	666	370	Brown-Rytlewski & Wilson 2005
Peak adult emerg.	Troy MI	2004	6/22 - 6/29	894	1027	961	534	Brown-Rytlewski & Wilson 2005
Peak adult emerg.	OH and MI	2011-2012	average			855	475	Duarte 2013
Peak adult emerg.	Newark, DE	2021	4-Jun			574	319	Duan 2021
Peak adult emerg.	SouthCen. MI	2019	average			914	508	Petrice 2021

4. Peak adult activity

Event	Area	Year	Dates	DDF low	DDF high	DDF	DDC	Reference
Peak adult activity	Whitemore, MI	2005	24-Jun					Rodriguez-Saona et al. 2007
Peak adult activity	Lansing MI	2006	7/1 - 7/21	1060	1380	1220	678	Tluczek et al. 2011 (wrongly reported in DDF?)
Peak adult activity	Lansing MI	2007	15-Jun			920	511	Tluczek et al. 2011 (wrongly reported in DDF?)
Peak adult activity	Knoxville TN	2016-2017	average			1000	556	Palmer 2018
Peak adult activity	Central MD	2017	6/9 - 6/15			1481	823	Abell et al. 2019
Peak adult activity	8 sites in MI	2006-2008	lt. 6/mid 7			1800	1000	Poland et al. 2011 (800-1200 DDC)
Peak adult activity	southeast MI	2014	late Jun to early Jul					Robinett et al. 2021 (specific dates not provided)
Peak oviposition*	SE MI	2003	lt. 6/erl. 7			1424	791	Bauer et al. 2004; Cappaert et al. 2005
Mean adult activity^	Essex Co. ON	2003	erl-mid Jul			1829	1016	Lyons et al. 2004*

5. End adult activity

Event	Area	Year	Dates	DDF low	DDF high	DDF	DDC	Reference
End adult activity	Central MD	2017	13-Jul			2342	1301	Abell et al. 2019
End adult activity	SouthCen. MI	2019	average			1461	812	Petrice 2021
End adult activity	8 sites in MI	2006-2008	end of Jul			2520	1400	Poland et al. 2011 (averages for 3 yrs)
End adult activity	8 sites in MI	2007	10-Aug			3479	1933	Poland et al. 2011 (Table 4)

*synthetic (avg 25-Jun to 15-Jul) - PRISM data converted to DD using uspest.org; file=LANSINGMI03.txt
^synthetic (avg Jul-1 to Jul-15) - PRISM data converted to DD using uspest.org; file=SOUTHGATEMI03.txt

6. Emergence to oviposition

Event	Area	Year	Dates	DDF	DDC	Reference
Emerg. to ovip.*	SE MI	2003	6/6 - 7/1	413	229	Bauer et al. 2004

*synthetic - Lansing (diff of DD between Jun-6 and Jun-25)
assume mating occurs w/in 10 days of emergence; ovip ~9 days later (7-10); so diff of DD btwn Jun-6 and Jun-24

7. Egg hatch

Event	Area	Year	Dates	DDF	DDC	Reference
Eggs hatch*	SE MI	2003	July and early Aug	1071	556	Bauer et al. 2004

8. Larval development

Event	Area	Year	Dates	DDF	DDC	Reference
Beg. larval devel.	Knoxville, TN	2016-2017	average	1783	991	Palmer 2018
Peak larval devel.	Knoxville, TN	2016-2017	average	2948	1638	Palmer 2018
Peak larval devel.	Central MD	2017		3056	1698	Abell et al. 2019
Peak larval devel.	Syracuse, NY	2015-2017	average	2160	1200	Jones et al. 2020 (1-yr life cycle insects)
Beg. J-larva devel.	Knoxville, TN	2016-2017	average	3157	1754	Palmer 2018
J-larva devel.	Central MD	2017		4878	2710	Abell et al. 2019

9. Pupal development

Event	Area	Year	Dates	DDF	DDC	Reference
Pupal development	North NC	2017-2020	28-Feb	252	140	Nalepa 2021 (Table 1)

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Robinett, M. A., T. M. Poland, and D. G. McCullough. 2021. Captures of emerald ash borer (Agrilus planipennis) adults in post-invasion white ash sites with varying amounts of live phloem. Forests 12:262.

Rodriguez-Saona, C. R., J. R. Miller, T. M. Poland, T. M. Kuhn, G. W. Otis, T. Turk, and D. L. Ward. Behaviors of adult *Agrilus planipennis* (Coleoptera: Buprestidae). The Great Lakes Entomologist. 40:1-16.

Tluczek, A. R., D. G. McCullough, and T. M. Poland. 2011. Influence of host stress on emerald ash borer (Coleoptera: Buprestidae) adult density, development, and distribution in *Fraxinus pennsylvanica* trees. Environmental Entomology 40:357–366.

B12. Comparison / synthesis of all field-collected data

	First adult emergence	50% adult emergence	Peak adult emergence	Peak adult activity	End adult activity	Emerg. to oviposition	Egg hatch
Mean	263	458	434	611	1361	229	556
Min	161	390	319	319	812		
Max	348	508	508	1016	1933		

	First larval develop.	Peak larval develop.	Pupal devel.	Beginning J-larva dev.
Mean		1512	140	2710
Min		1200		
Max		1698		

Based on distro of adult emergce DDs and assuming pupa req 116 DDCs, then the cohort distro for OW pupa is mean = 146 DDs (min = 44, max = 232)
Pupal development period in line with lab studies (140 vs. 125 DDC)
Adult emergence to OV very consistent with Pre-OV to OV in lab study (229 vs. 236 DDC)
Start of adult emergence lower than J-larva to adult DDS estimated in lab studies (262 vs. 326 DDC)

CLIMATE SUITABILITY MODEL

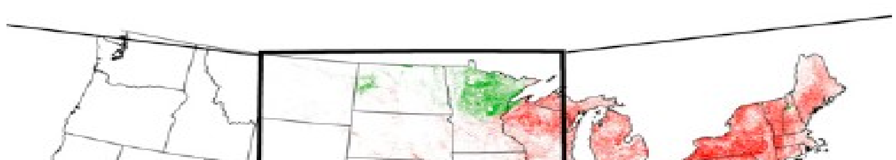
1. Crosthwaite, J. C., S. Sobek, D. B. Lyons, M. A. Bernards, and B. J. Sinclair. 2011. The overwintering physiology of *the emerald ash borer, Agrilus planipennis* Fairmaire (Coleoptera : Buprestidae). Journal of Insect Physiology 57:166-173.
- Prepuae (J-larvae) can survive temps as low as -30C
- Overwintering mortality may limit EAB's distro where temps annually decline below ~ -30C
- Areas with regular exposure to temps < -35C may provide thermal refugia for ash
- Before the onset of cold temperatures, molecules for cold tolerance accumulate and cuticular waxes reduce the inoculation by ice
- Antifreeze agents are necessary to depress the supercooling point
- The supercooling point in North America is as low as -35.3C

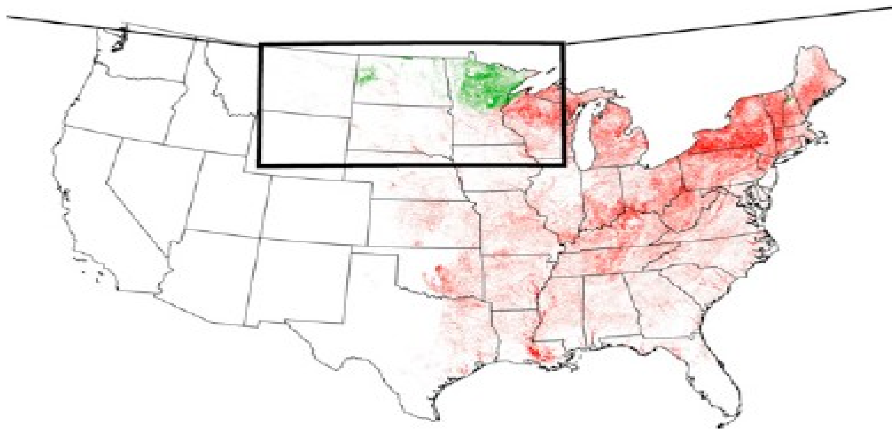
2. Christianson, L. D. E. and R. C. Venette. 2018. Modest effects of host on the cold hardiness of emerald ash borer. Forests 9:346.
- Investigated effects of black and green ash on the cold hardiness of EAB
- Found little difference according to host species, although larvae from black ash were sometimes less cold hardy
- Overwintering mortality may limit EAB's distro where temps annually decline below ~ -30C
- Areas with regular exposure to temps < -35C may provide thermal refugia for ash

3. Cuddington, K., S. Sobek-Swant, J. C. Crosthwaite, D. B. Lyons, and B. J. Sinclair. 2018. Probability of emerald ash borer impact for Canadian cities and North America: a mechanistic model. Biological Invasion 20:2661-2677.
- Produce a mechanistic model of OW mortality of EAB prepupae to identify Canadian cities and areas of NA at risk of impact
- Used a linear regression equation to predict underbark temperatures and predicted return time of weather events cold enough to cause 99% or 75% mortality
- Found that most of NA does not experience extreme cold events frequently enough to prevent ash mortality (i.e.more frequently than every 6 years)

4. DeSantis, R. D., W. K. Moser, D. D. Gormanson, M. G. Bartlett, and B. Vermunt. 2013. Effects of climate on emerald ash borer mortality and the potential for ash survival in North America. Agricultural and Forest Meteorology. 178-179:120-128.
- Combined USDA FIA ash data, climate, and bark temperature data to model the potential surival ability of EAB in range of green, white and black ash
- Conservative estimates of coldest temp experiencec by EAB should account for buffering capacity of snow cover and tree bark

- Distribution model shows presence of EAB in all areas in the range except those experiencing temps < 30C in northern MN and ND (see below)





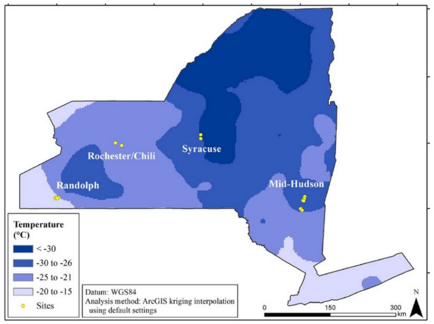
(taking into account buffering effects of tree bark). Red indicates areas where ash is present
and EAB experiences temps ≥ 30C (taking int account buffering effects of bark).
Note: EAB is now in Duluth, MN, an area they predicted to be unsuitable.

5. Fick, W. E., and C. J. K. MacQuarrie. 2018. An artifical delay in emergence influences the number but not the fitness of adult emerald ash borer emerging from infested ash wood. Entomologia Experimentalis et Applicata. 166:171-182.

- Subjected infested logs to 7-14 cold storage and quantified no. that emerged, time to emergence, and body condition of adults
- No. of adult beetles emerging decreased with cold storage time, but fat and water content in emerging adults did not decrease
- Adult emergence time increased as cold storage time increased
- They did not rear the insects at a constant temperature so data on emergence cannot be used for model development

6. Jones, M. I., J. R. Gould, and M. K. Fierke. 2017. Mortality of overwintering emerald ash borer (Coleoptera:Buprestidae) associated with an extreme cold event in New York, United States of America. Canadian Entomologist 486:482-486.

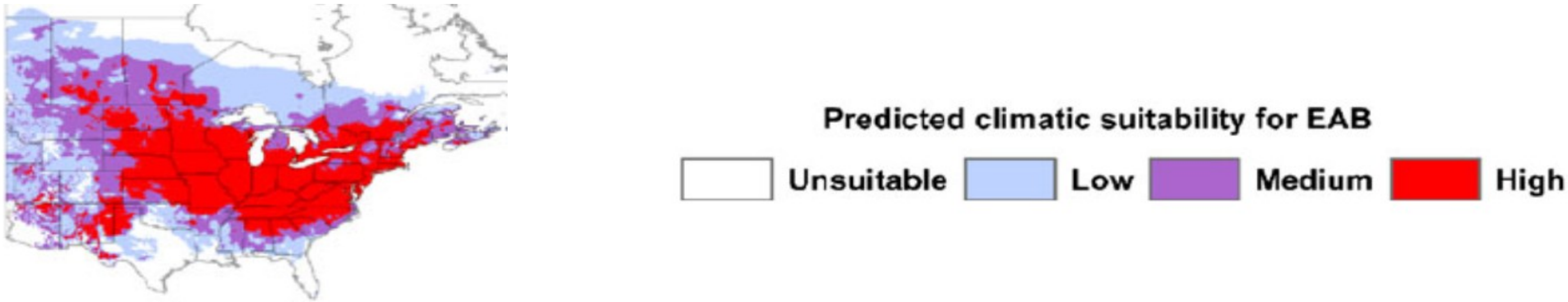
- Measured mortality at 3 sites in NY w/ severe winter temps from Feb 13-15 in 2016
- 93% mortality at the site (Syracuse) exposed to temps lower than -30C
- 75-80% mortality at the site exposed to temps of -26C to -30C
- <5 % mortality at the site exposed to temps s of -16C to -20C



7. Liang, L. and S. Fei. 2014. Divergence of the potential invasion range of emerald ash borer and its host distribution in North America under climatic change. Climatic Change 122:735-746.

- Used a correlative niche model (Maxent model) to predict climatic suitaiblity of EAB
- 33C is the upper temperature limit based on their models

- Min temp of June contributed most (>50%) to the model
- Predicted high to moderate suitability in most eastern/midwestern states under current climate conditions (see below)



8. MacQuarrie, C. J. K., B. J. Cooke, and R. Saint-Amant. 2019. The predicted effect of the polar vortex of 2019 on winter survival of emerald ash borer and mountain pine beetle. Canadian Journal of Forest Research 49:1165-1172.

- Used simulation models of the winter biology of EAB (and mtn. pine beetle) to illustrate the anticipated effect of the 2019 winter polar vortex on OW survival
- Figures 1 and 4 are shown below
- Mortality predicted in MN, Manitoba (Winnipeg), and Ontario (Thunder Bay), but cold was not predicted to impact pops in eastern North America
- Currently there are only OW surival data for the pre-pupa stage
- The frequency of the 2-year life cycle varies across Canada and is hypothesized to increase with increasing latitude (data on this could improve model)

Fig. 1. (A) Relationship between minimum annual air temperature and minimum annual under-bark temperature for ash trees fit by linear (solid lines) and nonlinear (broken lines) models (see eqs. 2 and 3) using parameters derived by fitting models to data (black) and using parameters given in Cuddington et al. (2018) (gray); black circles show data digitized from Cuddington et al. (2018, fig. 3). (B) Modelled temperature dose response for emerald ash borer according to a logistic regression (solid line; eq. 1) fit to the data (grey circles) of Crosthwaite et al. (2011), as per Cuddington et al. (2018); black circles show cumulative mortality.

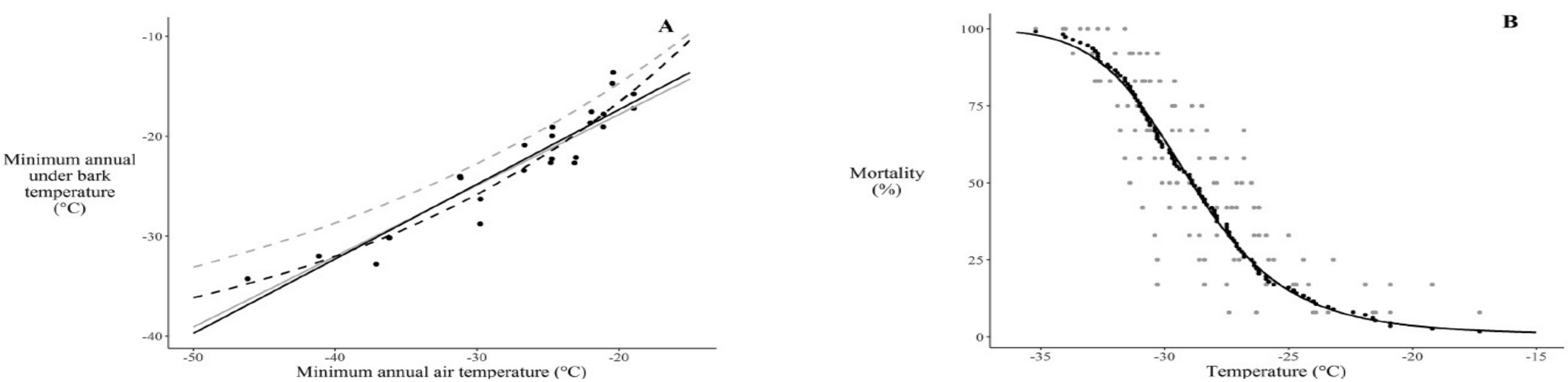
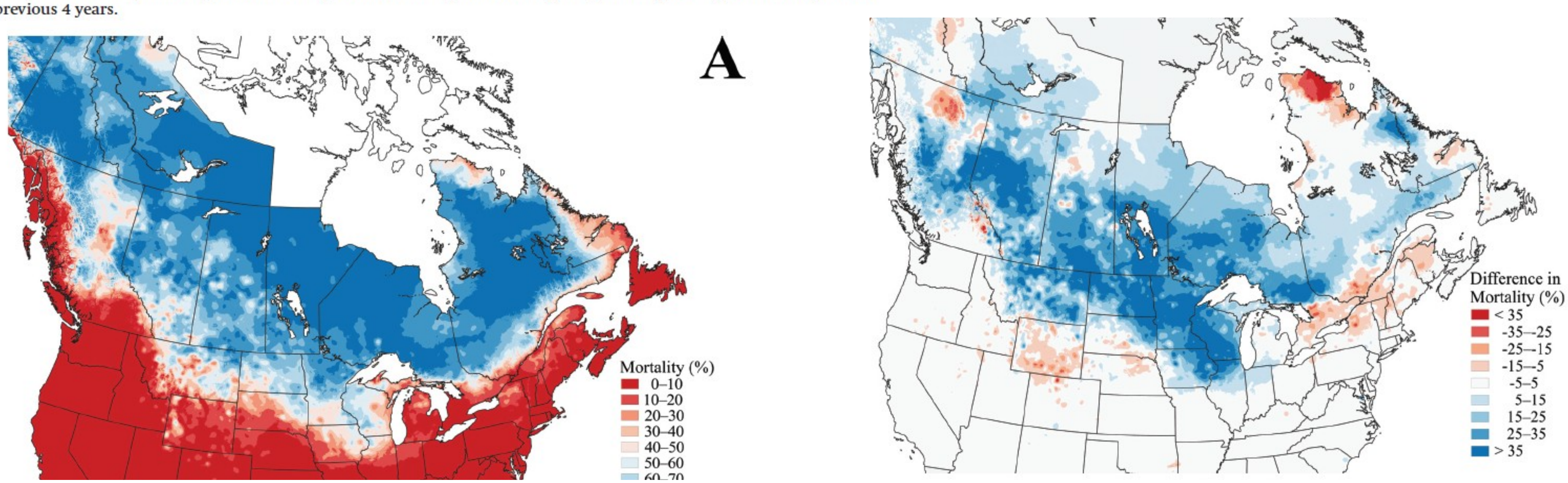


Fig. 4. (A) Predicted percent winter mortality of emerald ash borer, as of 10 March 2019, according to the logistic regression model of Cuddington et al. (2018) as implemented herein (see text for details), and (B) difference in predicted mortality between 2019 and the average predicted mortality for 2015–2018. In A, blue implies colder temperatures and higher mortality; in B, blue implies higher mortality in 2019 compared with the previous 4 years.

compared with the previous 4 years.

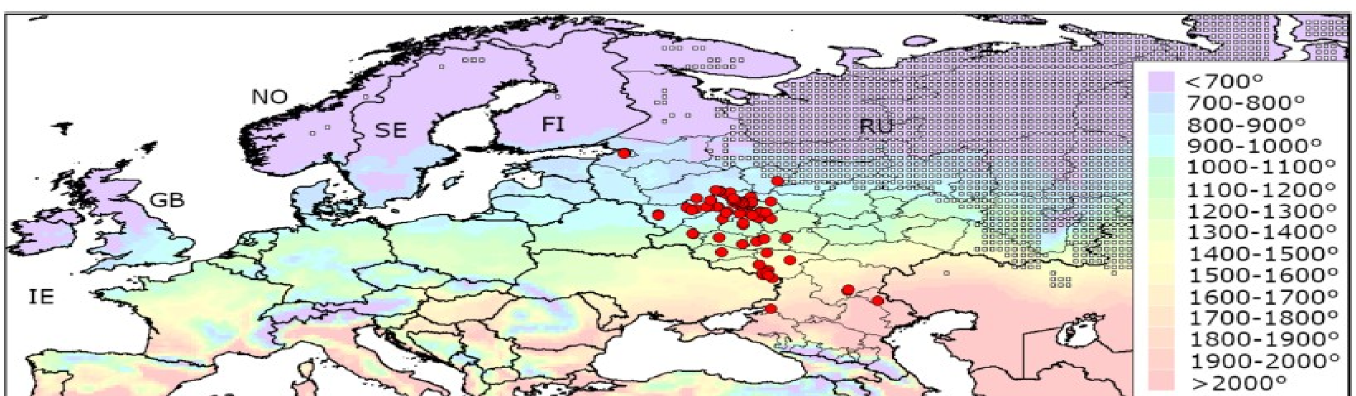


9. Orlova-Bienkowskaja, M. J., A. O. Bienkowski. 2020. Minimum winter temperature as a limiting factor of the potential spread of *Agrilus planipennis*, an alien pest of ash trees, in Europe

- No established population has been recorded in localities with temps <-34C
- This temp is close to the absolute supercooling point of larva (-35.3C)
- Unlikely that low temps could prevent invasion of northern western Europe (Sweden, Norway, Finland, etc) since temps were not <-34C from 2003-2019
- However such low temps are not rare in eastern European Russia (Kostroma, Vologoda, Orenburg regions etc.)

10. Orlova-Bienkowskaja, M. J., A. O. Bienkowski. 2022. Low heat availability could limit the potential spread of the emerald ash borer to Northern Europe (prognonsis based on growing degree days per year). Insects 13:52.

- Mean annual growing DDs base 10C (AGDD10) was calculated for each cell of Earth's surface
- Minimum AGDD10 recorded in cells occupied by EAB was 714 deg for Asia, 705 deg in North America, and 711 deg in European Russia
- EAB has never been recorded in localities with AGDD10 below 700deg
- Concluded that ash (*Fraxinus excelsior*) in some parts of Norway, Sweden, Finland, Ireland, and Great Britain could escape EAB
- More data on the type of life cycle in Europe (1-yr vs. 2-yr) is needed
- Warming temps have contributed to northern range shifts of other Europe wood-boring pests, which suggests EAB could too
- Main conclusion: majority of Europe is climatically suitable for establishment



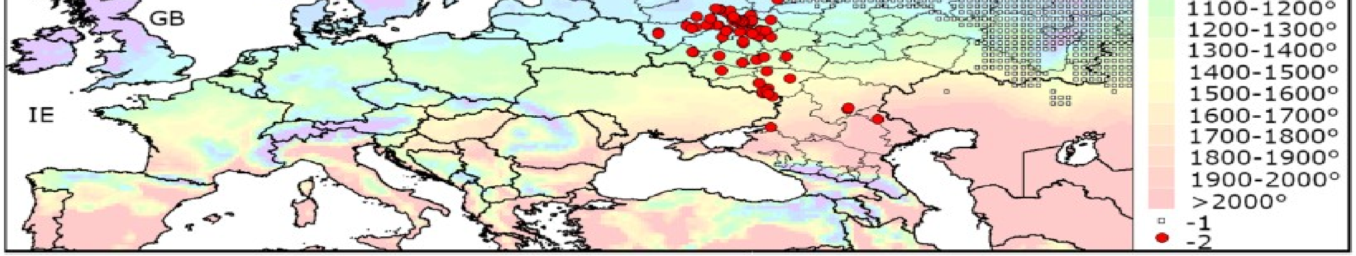


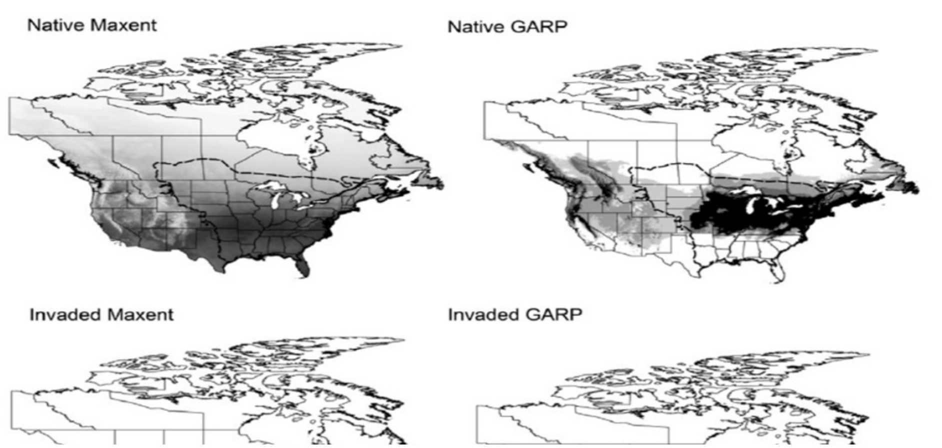
Figure 9. Distribution minimum winter temperature and heat availability in Europe. Mean $AGDD_{10}$ per year in 2003–2020 is indicated with colours (see the legend). 1—territories, which are not suitable for *Agrilus planipennis* establishment because of the extreme winter cold [15], 2—localities of *A. planipennis*. FI—Finland, GB—Great Britain, IE—Ireland, NO—Norway, RU—Russia, SE—Sweden.

11. Sobek, S., A. Rajamohan, D. Dillon, R. C. Cumming, and B. J. Sinclair. 2011. High temperature tolerance and thermal plasticity in emerald ash borer *Agrilus planipennis*. Agricultural and Forest Entomology 13:333-340

- EAB larvae were highly tolerant of elevated temps, w/ some instars surviving exposure to 56C
- High temp survival was increased by either slow warming or pre-exposure to elevated temps; this increased expression of heat shock protein (hsp70)
- Temps of 50C or higher resulted in complete mortality in 45 min
- This and other studies only investigated short-term survival or emergence, and did not account for sub-lethal consequences of high temp exposure; for example, reduced fecundity or sterility
- Larvea survive up to 53C but pupae survive only up to 51C

12. Sobek-Swant, S., D. A. Kluza, K. Cuddington, and D. B. Lyons. 2012. Potential distribution of emerald ash borer: What can we learn from ecological nice models using Maxent and GARP? Forest Ecology and Management 281:23-31.

- Correlative niche modeling study (GARP and Maxent) using native and US locality data
- GARP suitability maps (see below) show low suitability in northern parts of MN and ND
- Maxent predicted higher suitability when modeling with native range occurrences than models that used invaded range occurrences
- This older model is apparently not accurate for southern states - EAB occurs in several states there (SC, AR, GA, LA, etc.)
- The use of presence-only data from northern states in US probably explains this underprediction



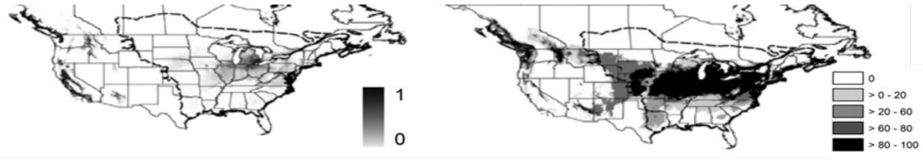


Fig. 2. Climatic suitability for EAB as predicted by Maxent and GARP ecological niche models.
Native: Model based on occurrence records from native range; Invaded: Model based on occurrence recrods from invaded range.

13. Venette, R. C. and M. Abrahamson. 2010. Cold hardiness of emerald ash borer, *Agrilus planipennis*: a new perspective. Pages 1-5 in Black ash symposium: proceedings of the meeting. U.S. Department of Agriculture, Forest Service, Chippewa National Forest, Bemidji, MN.

- Larvae exposed to -35C in lab experienced 90-95% mortality
- 90% mortality occurred outside after 5.5 wks when temp reached -34C
- Up to 70% mortality occurred outside after 5.5 wks when temp reached -28C
- Air temps are not necessarily the most reliable measure of the temp experienced by OW larvae (see also Desantis et al. 2013, Vermunt et al. 2012)
- Their simple model predicts the following results:

Deg F	Deg C	Perc. Mortality
0	-17.8	5
-10	-23.3	34
-20	-28.9	79
-30	-34.4	98

14. Vermunt, B., K. Cuddington, S. Sobek-Swant, J. C. Crosthwaite, D. Barry Lyons, and B. J. Sinclair. 2012. Temperatures experienced by woord-boring beetles in the under-bark microclimate. Forest Ecology and Management 269:149-157.

- Observed daily Tmin under-bark temps of ash trees at 6 sites in Ontario in winter of 2008-2009
- Overwintering EAB larvae experience temperatures warmer than ambient temps due to the buffering properties of snow and tree bark
- All means of daily under-bark Tmin were significantly higher and ranged from 1.5 to 2.9C for randomly selected trees
- Overall they found that temps under bark can be 2-7F (4C) higher than outside temps
- Diffs varied according the side of the tree - max under-bark temps on north side of trees in spring sim to max air temps, south sides were warmer
- Min under-bark temps were more variable from year-to-year within a tree than between trees within a location and year

15. DDRP climate suitability model (this study)

Analysis to derive the below parameters are presented in Barker et al. (2023)

DDRP Cold Stress	Value	Units
cold stress threshold	-31	C
limit 1 (mod. cold stress)	80	DDC
limit 2 (sev. cold stress)	160	DDC

DDRP Heat Stress	Value	Units
heat stress threshold	38	C
limit 1 (mod. heat stress)	75	DDC
limit 2 (sev. heat stress)	150	DDC