Phenology/Degree-Day Model Analysis – Jan. 23, 2020

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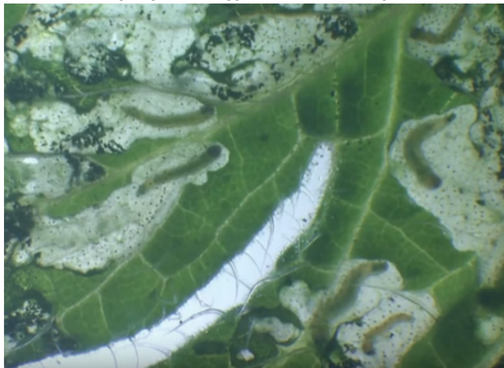
Tomato leafminer *Tuta absoluta* **(Meyrick 1917) (Lepidoptera: Gelechiidae)**

Hosts: Tomato, other Solanaceae (potato, eggplant) Native to: South America Invaded areas include: Mediterranean regions, W. Europe, India, Africa

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




Sources:

1. Cherif, A., S. Attia-Barhoumi, R. Mansour, L. Zappala, K. Grissa-Lebdi. 2019. Elucidating key biological parameters of *Tuta absoluta* on different host plants and under various temperature and relative humidity regimes. Entomologia Generalis 39:1-7.

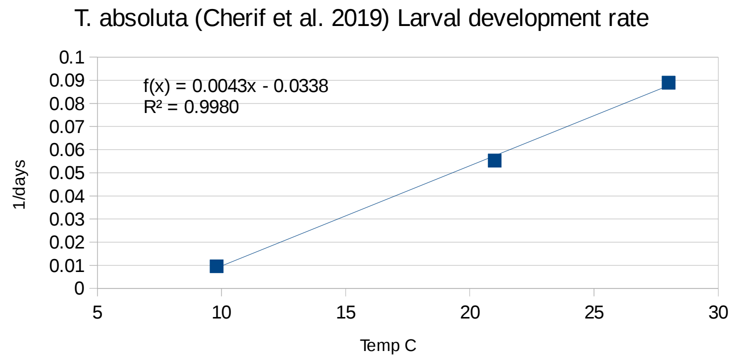
Methods: Re-analyze data from Figs. 1&2 to determine lower threshold and degree-day requirements with x-intercept method. Use a dummy data point to force x-intercept through proposed lower threshold of 7.78C/46F (data with yellow background).

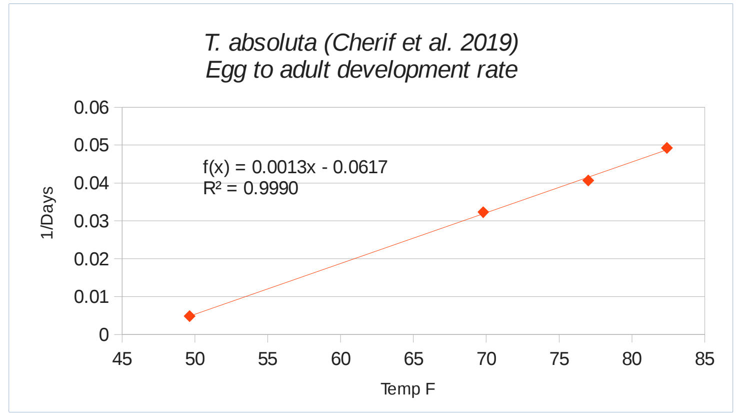
-Studies using Tunisian populations reared on tomato; not using data on development reared on potato and eggplant (which is slower)

From Tables 1 & 2 – Development rate vs. temperature on tomato at 3 temps for all stages except adult longevity (only 1 temp of 25C/77F)

-Notes: larval development at 25C (60% RH) is an apparent outlier; similarly only the 32% RH for 21 and 28C results are within range of all other studies; omit outlier point

			Egg		Larvae		Pupae			Egg to Adult			Adult Longev		
Avg. RH	Temp C	Temp F	Days	1/days	Days	1/days	Days	1/days	Temp F	Days	1/days		Days	DDs7.78C	DDs46F
	9.8	49.64	28.9	0.0346021	104.8	0.009542	59	0.016949	49.64	206	0.004854				
32.00%	21	69.8	3.39		18.08	0.0553097	9.49	0.105374	69.8	30.96	0.0323		11.33	195	351
60.00%	25	77	3.36	0.297619	15		6.22	0.160772	77	24.58	0.040683				
32.00%	28	82.4	2.88	0.3472222	11.24	0.088968	6.18	0.161812	82.4	20.3	0.049261		10.48	180	325
				Deg. F	Deg. C	Deg. F	Deg. C	F	Deg. C		Deg. F	Deg. C			
	slope			0.00957		0.00241		0.00469			0.00134	0.00241			
	intercept			-0.44005		-0.11088		-0.21583			-0.06168	-0.01878		**avg. R-sq**	
	R-sq			0.99996		0.99801		0.97453			0.99898	0.99898		0.9928696471	
	-a/b	(x-intercept)		46.0	7.78	46.0	7.78	46.0	7.78		46.0	7.78			
	-1/b	(DD reqs)		104.5	58	414.9	231	213.1	118		745.9	414.4		188	338





Results: At Tlow of 7.78C/46F, DD req.s for egg, larvae, pupae, egg to adult and adult longevity are: 55, 239, 118, 414, and 242 DDC, and 99, 431, 213, 746, and 435 DDF

2. Mahdi, K, S. Doumandji. 2013. Research on temperature: limiting factor of development of tomato leaf miner *Tuta absoluta* (Meyrik). Int. J. Agric. Sci and Res.
https://www.cabi.org/ISC/FullTextPDF/2014/20143099367.pdf

Notes: -performed in Algeria; reared on tomato foliage; average RH was 70% -they solved for an overall Tlow of 9.8C

Methods: Re-analyze data from Tables 2-3 to determine lower threshold and degree-day requirements with x-intercept method. Use a dummy data point to force x-intercept through proposed lower threshold of 10C/50F (data with yellow background).

	Days Development				
Temp C	Egg	Larvae	Pupa	Total	Adult Long
	144	500	300	580	164
15	12.1	23.0	36.4	71.5	26.7
21	6.2	13.3	13.4	32.9	12.1
30	4.1	7.9	6.5	18.5	6.47

		1/days	
	Temp F	**Egg**	
	48.22	0.0080	
	59.00	0.0826	
	69.80	0.1613	
	86.00	0.2439	
	slope:	0.00628	
	intercept:	-0.28877	
	R-sq:	0.99258	Deg. C
Tlow =	**-a/b**	**46.01**	**7.78**
Dds devel	**1/slope**	**159.3**	**89**

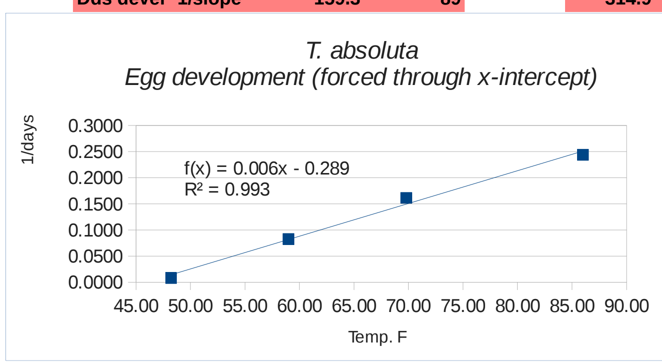
	1/days	
Temp F	**Larvae**	
47.06	0.002	
59.00	0.043478	
69.80	0.075188	
86.00	0.126582	
	0.00318	
	-0.14609	
	0.99915	Deg. C
	46.00	**7.78**
	314.9	**175**

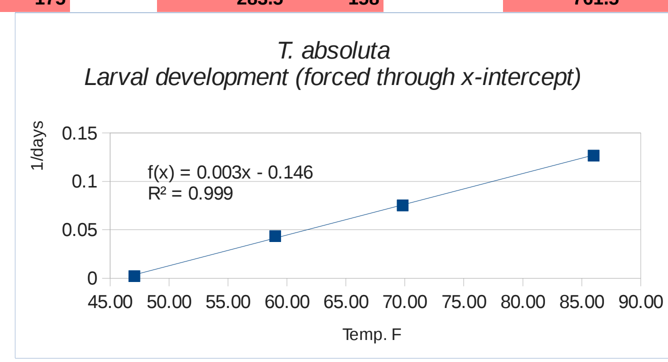
	1/days	
Temp F	**Pupae**	
42.70	0.0033333333	
59.00	0.0274725275	
69.80	0.0746268657	
86.00	0.1538461538	
	0.00353	
	-0.16222	
	0.93849	Deg. C
	46.00	**7.78**
	283.5	**158**

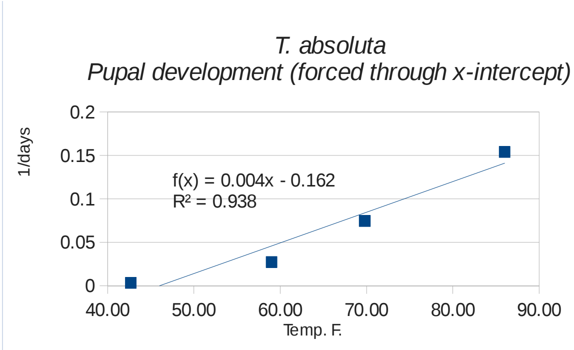
	1/days	
Temp F	**EggtoAdult**	
45.50	0.0017	
59.00	0.0140	
69.80	0.0304	
86.00	0.0541	
	0.00131	
	-0.06042	
	0.98812	Deg. C
	46.01	**7.78**
	761.5	**423**

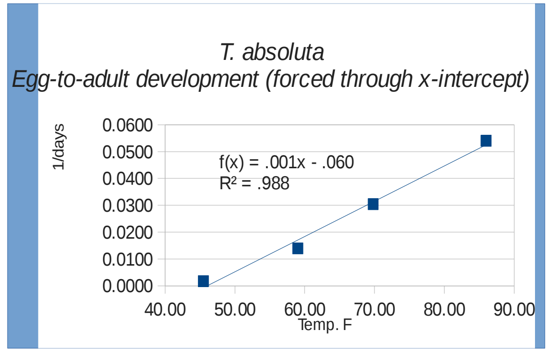
	1/days	
TempF	**Adult Longev.**	
44.91	0.0050	
59.00	0.0375	
69.8	0.0826	
86.0	0.1546	
slope:	0.00369	
intercept:	-0.16990	
R-sq:	0.97878	Deg. C
-a/b	**46.00**	**7.78**
1/slope	**270.7**	**150**

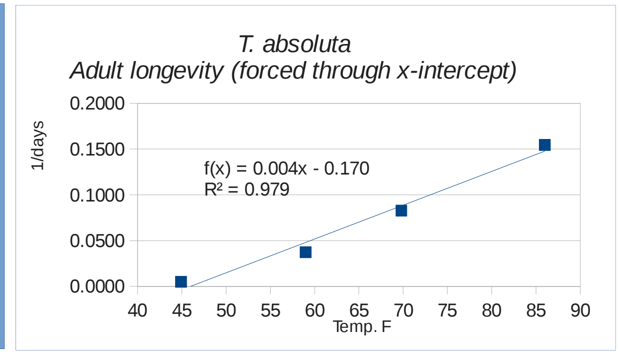
avg. R-sq
0.9795871









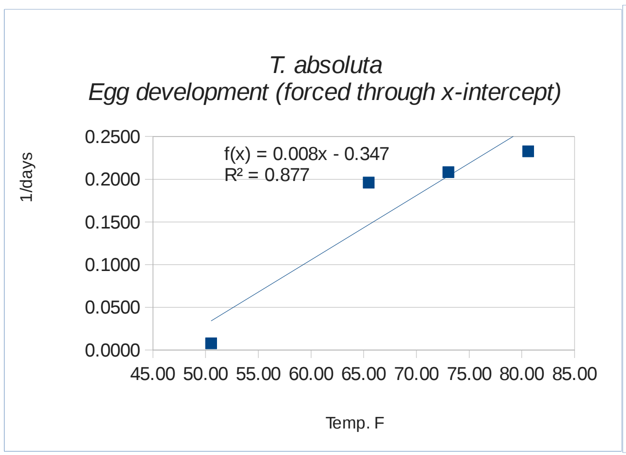


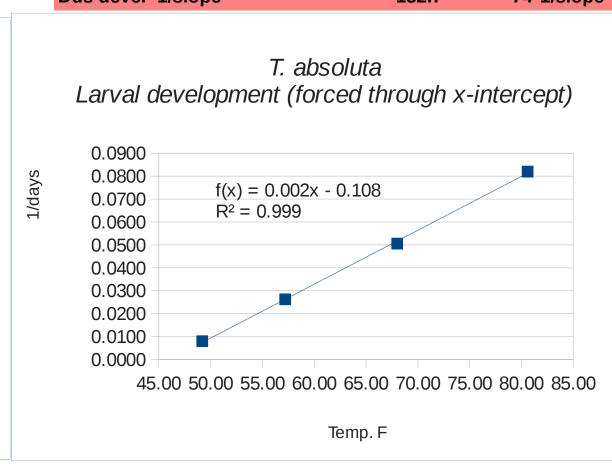
Results: At Tlow of 7.78C/46F, DD req.s for egg, larvae, pupae, egg to adult and adult longevity are: 89, 175, 158, 423 and 150 DDC, and 159, 315, 283, 762, and 271 DDF

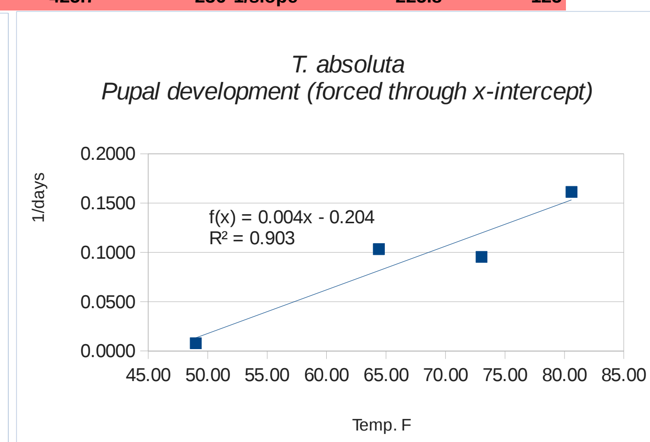
-further analysis from citations cited in discussion section:

Refs:	**Haji et al 1988, Coelho & Franca 1987**	**Estay 2000**	**Haji et al 1988, Coelho & Franca 1987**
		Days development	
Temp C	Egg	Larvae	Pupae
18.6	5.1		
22.8	4.8		
27	4.3		
14		38.1	
20		19.8	
27		12.2	
18			9.7
22.8			10.5
27			6.2

		1/days			1/days			1/days		
	Temp F	**Egg**		Temp F	**Larvae**		Temp F	**Pupae**		
	50.52	0.0080		49.20	0.0080		49.00	0.0080		
	65.48	0.1961		57.20	0.0262		64.40	0.1031		
	73.04	0.2083		68.00	0.0505		73.04	0.0952		
	80.60	0.2326		80.60	0.0820		80.60	0.1613		
	slope:	0.00753		slope:	0.00235		slope:	0.00443		
	intercept:	-0.34662		intercept:	-0.10807		intercept:	-0.20381		**avg. R-sq**
	R-sq:	0.87741	Deg. C	R-sq:	0.99932	Deg. C	R-sq:	0.90321	Deg. C	0.9266
Tlow =	**-a/b**	**46.01**	**7.78**	**-a/b**	**46.01**	**7.78**	**-a/b**	**46.01**	**7.78**	
Dds devel	**1/slope**	**132.7**	**74**	**1/slope**	**425.7**	**236**	**1/slope**	**225.8**	**125**	







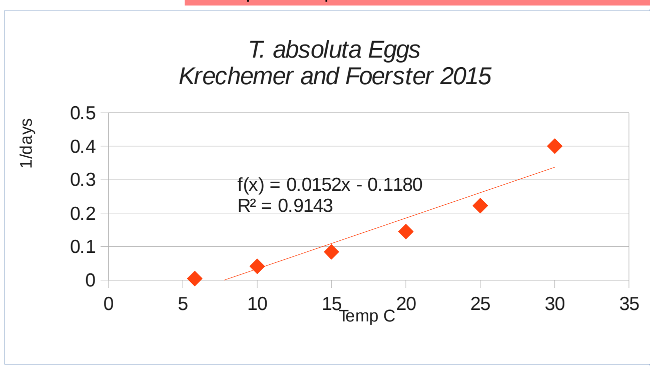
Estim. egg to adult development time: 436 DDC7.78 784 DDF46

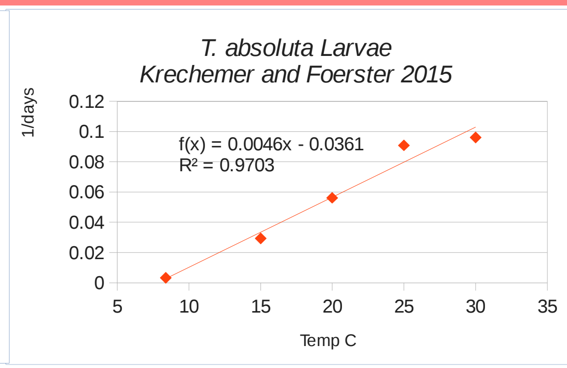
Results: At Tlow of 7.78C/46F, DD req.s for egg, larvae, pupae, and egg to adult were: 74, 236, 125 and 436 DDC, and 133, 426, 226, and 784 DDF

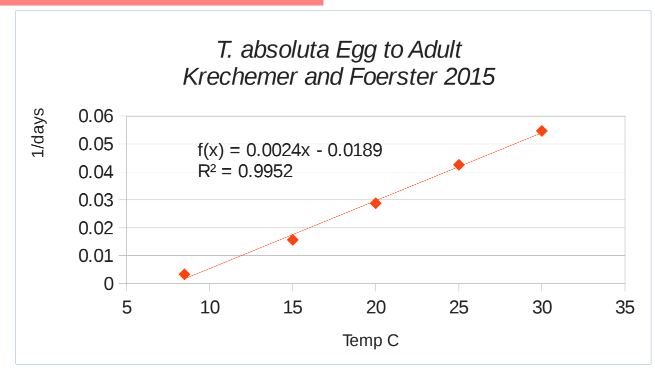
3. Krechemer F.S. and L.A. Foerster. 2015. *Tuta absoluta* (Lepicoptera: Gelechiidae): Thermal requirements and effect of temperature on development, survival, reproduction and longevity. Eur. J. Entomol. 112:658-663.

- Reared on tomato (cult. Santa Clara) in Colombo, Southern Brazil 25 deg. South Lat.
- Methods: use x-intercept method to verify lower threshold and DD requirements for all stages studied.
- Results: solved a common Tlow of 8C, and Tupper of 37.3.

		Eggs			**Larvae**			**Pupae**			**Egg to Adult**			
Temp C	**Temp F**	**Days**	**1/days**	**Temp C**	**Days**	**1/days**	**Temp C**	**Days**	**1/days**	**Temp C**	**Days**	**1/days**		
5.8		225	0.0044444	8.38	300	0.003333	8.93	250	0.004	8.48	300	0.0033333333		
10	50	24.4	0.0409836	10	56.4		10	36.8	0.027174	10	115.4			
15	59	11.9	0.0840336	15	34.1	0.029326	15	18.4	0.054348	15	63.9	0.0156494523		
20	68	6.9	0.1449275	20	17.8	0.05618	20	10.2	0.098039	20	34.8	0.0287356322		
25	77	4.5	0.2222222	25	11	0.090909	25	8.4	0.119048	25	23.5	0.0425531915		
30	86	2.5	0.4	30	10.4	0.096154	30	5.4	0.185185	30	18.3	0.0546448087		
	slope		0.0151662			0.00464			0.007836			0.0024326854		
	intercept		-0.117995			-0.036119			-0.06097			-0.018930889		**average R-sq**
	R-sq:		0.9143317			0.970307			0.97714			0.995177156		0.964238979
Tlow	-a/b		7.780156	DDF46		7.784028	DDF46		7.780291	DDF46		7.781889243	DDF46	
DDReq	1/slope		65.9	118.7		215.5	387.9		127.6	229.7		411.1	739.9	





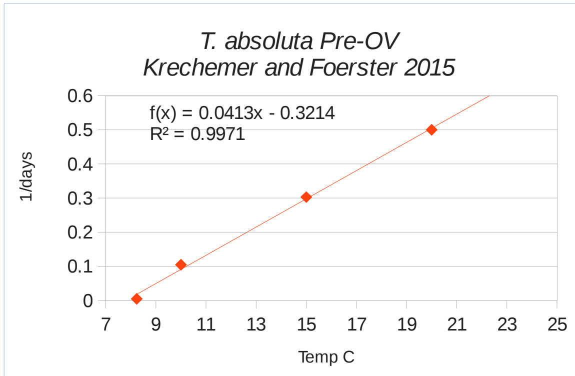


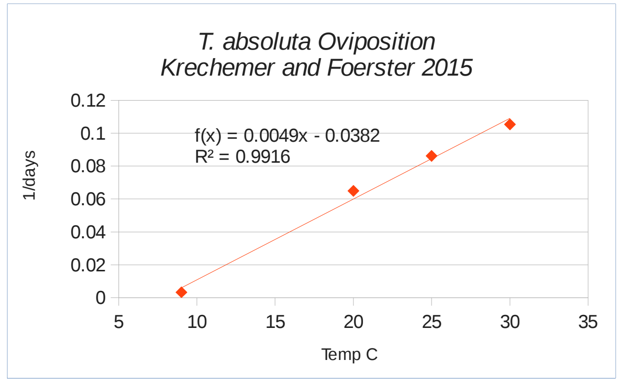
Results: At Tlow of 7.78C/46F, DD req.s for egg, larvae, pupae, and egg to adult were: 66, 216, 128 and 411 DDC, and 119, 388, 230, and 740 DDF

	Pre-OV				**Oviposition**	
Temp C	Days	1/days		Temp C	Days	1/days
8.23	200	0.005		9.02	300	0.003333
10	9.5	0.1052632		10	14.5	
15	3.3	0.3030303		15	14.6	
20	2	0.5		20	15.4	0.064935
25	2.3			25	11.6	0.086207
30	1.9			30	9.5	0.105263

		Pre-OV		Oviposition	
	slope	0.0413108		0.004911	
	intercept	-0.32142		-0.038214	
	R-sq	0.997131		0.991588	
Tlow	-a/b	7.7805315	DD46F	7.781859	DD46F
DDReq	1/slope	24.2	43.6	203.6	366.5

average R-sq
0.994359





Results: At Tlow of 7.78C/46F, DD req.s for Pre-OV and ovipostition were: 24 and 204 DDC, and 44 and 367 DDF

4. Barrientos, R., J. Apablaze, A. Norero, P. Estay. 1998. Threshold temperature and thermal constant for development of the South American tomato moth, *Tuta absoluta* (Lepidoptera: Gelechiidae). Ciencia e Inv. Agr. 25:133-137.

- Studies in Santiago, Chile (Pontificia University), ca 33.5 S. Latitude; reared on tomato
- Reported Tlow values of 6.9, 7.6, 9.2, and 8.14C for egg, larvae, and pupae, and egg to adult development
- Methods: same analysis as sources above. Use Table 6 which used calculated average temperatures.

		Eggs			**Larvae**			**Pupae**			**Egg to Adult**		
Temp C	**Temp F**	**Days**	**1/days**	**Temp C**	**Days**	**1/days**	**Temp C**	**Days**	**1/days**	**Temp C**	**Days**	**1/days**	
8.85	47.93	138.2	0.0072359	9.1	190.75	0.0052425	8	133.2	0.0075075	9	328.45	0.003045	
14.47	58.046	14.08	0.0710227	13.88	38.02	0.0263019	13.65	24.2	0.0413223	14	76.3	0.013106	
19.77	67.586	7.88	0.1269036	19.67	19.88	0.0503018	19.67	12.06	0.0829187	19.7	39.82	0.025113	
27.21	80.978	5.13	0.1949318	27.14	12.22	0.0818331	27.1	6.48	0.154321	27.1	23.83	0.041964	
		slope	0.010212			0.0042328			0.0076695			0.002152	
		intercept	-0.079452			-0.032932			-0.059669			-0.01674	
		R-sq	0.9972365			0.9998877			0.9871832			0.999175	
	Tlow	-a/b	7.7803	DDF46		7.7801	DDF46		7.7801	DDF46		7.7800	DDF46
	DDReq	1/slope	97.9	176.3		236.3	425.3		130.4	234.7		464.7	836.5

average R-sq
0.995870547

Results: At Tlow of 7.78C/46F, DD req.s for egg, larvae, pupae, and egg to adult were: 98, 236, 130 and 465 DDC, and 176, 425, 235, and 837DDF

overall avg. R-sq
0.975595685

5. Erdogan, P. and N.E. Babaroglu. 2014. Life table of the tomato leaf miner, *Tuta absoluta* (Meyrick)(Lepidoptera: Gelechiidae) J. Agric. Faculty of Gaziosmanpasa Univ. http://ziraatdergi.gop.edu.tr/Makaleler/1840340134_80-89.pdf

- Studies using NW Turkish population (Beypazari Ankara) reared on tomato
- RH was 65+/-5%

From Table 2 &3: (females; maies similar but not used here):

		Egg	L1	L2	L3	L4	Larvae total	pupae	Egg to Adult	Adult Longevity	Pre-OV	Ov period
Temp C	Days	3.96	2.49	2.32	2.52	3.79	11.0	9.53	30.18	18.16	1.28	7.88
25.5	DDC7.78:	70	44	41	45	67	194	169	535	322	23	140
Temp F												
77.9	DDF46	126	79	74	80	121	350	304	963	579	41	251

Results: At Tlow of 10C/50F (only one temperatture of 25.5C used), DD req.s for egg, larvae, pupae, egg to adult and adult longevity are:
61, 170, 148, 468 and 281 DDC, and 110, 306, 266, 842, and 507 DDF
Also, at Tlow of 10C/50F, DD req.s for adult pre-OV and OV period are: 20 and 122 DDC, and 36 and 220 DDF
Also, at Tlow of 10C/50F, DD req.s for L1, L2, L3, and L4 are: 39, 36, 39, and 59 DDC, and 69, 65, 70, and 106 DDF

6. Sylla, S., T. Brevault, L. Monticelli, K. Diarra, and N. Desneux. 2019. Geographic variation of host preference by the invasive tomato leaf miner *Tuta absoluta:* implications for host range expansion. J. Pest Sci. 92:1387-1396. https://pubag.nal.usda.gov/catalog/6563098

-Methods: estimate egg to adult development times assuming lower threshold of 10C/50F

From Table 2 – egg to adult devel time for populations from France and Senegal on six solanaceous plants.

At 25 deg C (+/-1degC), 65% RH (+/-10%), 16hr daylength

Host Plant		France	Senegal	
S. lycopersicum	tomato	**25.2**	**21.2**	
S. melangena	eggplant I	**30.6**	**25.3**	
S. tuberosum	potato	**28.4**	**25.1**	
S. aethiopicum	eggplant I	28.7	28.5	
C. annuum	non preferred			
C. frutescens	all died			
Mean		28.2	25.0	Days
		500	443	DDC7.78
		900	798	DDF46

-Results: egg to adult development estimates are 500 DDC/900 DDF (France) and 443 DDC/798 DDF (Senegal)

For tomato only:	434	DDC7.78	365	DDC7.78
	781	DDF46	657	DDF46

7. Pereyra, P. and N. Sanchez. 2006. Population parameters of the tomato leaf miner, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) Neotropical Entomol. 35:671-6.

- Studies with populations in Argentina; Mostly life table params for tomato and potato hosts at one temp (25C/77F)

-Methods: analyze data in Table 1 to determine developmental requirements of larvae at 25C and 60% RH

Host Plant		**Days Larval Devel.**	**DDC7.78**	**DDF46**
S. lycopersicum	tomato	12.4	214	384
S. tuberosum	potato	14	241	434

Results: Larval development required ca. 214 and 241 DDC7.78 and 384 and 434 DDF46 for tomato and potato host plants, respectively.

8. Mansour, R., A. Cherif, S. Attia-Barhoumi, L. Zappala, K. Grissa-Lebdi. 2019. *Tuta absoluta* inTunisia: ten years of invasion and pest management. Phytoparasitica 47:461-474.

- In NE Tunisia can develop 4 generations between Nov and May
- 3 male flight peaks between Jan. and May **(**Cherif et al. 2013**)**
- Between Mar and July, 4-5 male flight peaks w/higher activity in summer, and 3 gens for eggs and larvae in open-field tomatoes in NE Tunisia [Cherif and Grissa-Lebdi (2017)]

9. Asma, C. and K. Lebdi-Grissa. 2017. Population dynamics of the tomato leaf miner Tuta absoluta (Meyrick) (Lepidoptera: Gelechiidae) in Tunisia natural conditions. J. Ent and Zoo Studies 5:427-432.

- In NE Tunesia (Bou Slim, Zaghouan Province) 5 generations April, May, June, July and August (monitoring began in April)
- In Takelsa (Nabeul Province) had 4 peaks/generations during this same time; catch more frequent during summer hotter months, up to 380 males/trap/week

From Table 2 avg Temps, can estimate rough DDs for each month:

Zaghouan 2014: (Bou slim)

	April	May	June	July	Aug	AVG	DDC/gen
Temp C	16.7	19.5	25.2	27.2	28.60	23	DDF/gen
DDC7.78:	268	352	523	583	625	470	← 5 peaks and claim this equals 5 gen.s during this period so rough avg 470 DDC/gen = 846 DDF/gen
DDF46						846	Alternatively, 4 gens during this time would be:575 DDC/gen = 1035 DDF/gen – better matching Sources #1&2 above

Nabeul 2016 (Takelsa)

						AVG	
Temp C	20.4	19.5	23.2	26.3	26.2	23	
DDC7.78:	379	352	463	556	553	460	← 4 peaks assume equals 4 gen.s: 460 DDC/gen = 828 DDF/gen – good match sources 1&2 above
DDF46						828	

- Results: possibly 575 DDC/gen in Zaghouan and 460 DDC/gen in Takelsa, populations higher in Takelsa perhaps assoc. with higher RH levels (avg 68% vs. 37%)

10. Rasheed, V.A., S.R.K. Rao, T.R. Babu, T.M. Krishna, B.V.B. Reddy, and G.M. Naidu. 2018. Biology and morphometrics of tomato pinworm, *Tuta absoluta* (Meyrick) on tomato. Int. J. Curr. Microbiol. App. Sci. 7:3191-3200

- Studies in Tirupati, India at 25+/-2 deg. C and 75+/-2% RH
- Methods: Determine temperature vs development rates based on results in Tables 1& 2.

	Egg	Larvae	Pupae	Egg to Adul	Pre-OV	Ovipos	25% OV	Post-OV	Female Lon	ELP+PreOV+25%OV
Days	4.14	12.25	7.81	24.19	1.6	6.2	1.24	2.55	14.75	27.03
Est DDC7.78	71.3	210.9	134.5	416.6	27.6	106.8	21.4	43.9	254.0	465.5
Est DDF46	128.3	379.7	242.1	749.8	49.6	192.2	38.4	79.0	457.2	837.8

	L1	L2	L3	L4	L1-4
Days	2.08	2.75	3.56	3.86	12.25
Est DDC7.78	35.8	47.4	61.3	66.5	210.9
Est DDF46	64.5	85.2	110.3	119.6	379.7

- Results: estimates from a single temp (25C) but includes adult pre-OV, OV, post-OV, and longevity

11. Summary table for tomato as host	Egg		Larvae		Pupae		Egg to Adult		Pre-OV		OV (or adult longev)		E+L+P+PreOV+20%OV	
Source:	**DDC7.78**	**DDF46**	**DDC7.78**	**DDF46**	**DDC7.78**	**DDF46**	**DDC7.78**	**DDF46**	**DDC7.78**	**DDF46**	**DDC7.78**	**DDF46**	**DDC7.78**	**DDF46**
1. Cherif et al. 2019 (Tunisia)	58	105	231	415	118	213	414	746			188	338	492	885
2a. Mahdi, K, S. Doumandji 2013 (Algeria)	89	159	175	315	158	284	423	761			150	270.7	489	880
2b. data cited in above source	74	133	236	426	125	226	436	784						
3. Krechemer and Foerster 2015 (Brazil)	66	119	216	388	128	230	411	740	24.2	43.6	204	366.5	474	853
4. Barrientos et al. 1998 (Chile)	98	176	236	425	130	235	465	837						
5. Erdogan and Babaroglu 2014 (Turkey)	70	126	194	350	169	304	535	963	23	41	140	251	484	871
6. Sylla et al. 2019 (France and Senegal)							434	781						
7. Pereyra and Sanchez 2006 (Argentina)			214	384										
9a. Asma and Lebdi-Grissa 2017A (Zaghouan Tunisia)													470	846
9b. Asma and Lebdi-Grissa 2017B (Nabeul Tunisia)													460	828
10. Rasheed et al. 2018 (India)	71	128	211	380	134	242	417	750	28	50	150.7	271.2	474	854
Averages	75	135	214	385	138	248	442	795	25	45	166	300	478	860
St. Dev.	13.6	24.5	21.4	38.5	18.5	33.3	41.3	74.4	2.5	4.5	27.7	49.8	11.1	20.0
CV	18.2	18.2	10.0	10.0	13.4	13.5	9.4	9.4	10.0	10.0	16.6	16.6	2.3	2.3
mean C.V.	11.4	(compare to using 10C/50F as lower threshold mean C.V. = 13.7)												

12. Model Stages Summary

Species:	*Tuta absoluta*			
Common Name & abbrev:	Tomato leafminer (TABS)			
Country of Origin, data from:	South America (S. Brazil, Chile) – native region and Tunisia, Algeria, Turkey, France, Senegal – invaded regions			
Pest of:	Vegetables including tomato, eggplant and peppers			
Validation Status:	Not validated; no spring activity data available to calibrate model initialization (this model is therefore conservative and may predict too early)			
	Deg.s (C)	**Deg.s (F)**		**Notes:**
Lower Threshold:	7.78	46		Best overall Tlow for all stages, Pre-OV & OV may be slightly higher
Upper Threshold:	35.00	95		Martins et al. High egg mortality above 30C/86F; but account for diff. in canopy temps vs weather shelters
Calculation Method:		Single Sine		
Model Start:		January 1st		Temperate adapted species OW in reproductive diapause, may become active around 12hr Daylength (ca. Mar 20)
Degree-Day Requirements	**DDs (C)**	**DDs (F)**		
Egg	75	135		
Larvae	214	385		
Pupae	138	248		
Egg-to-Adult	442	795		
Pre-OV	25	45		
Oviposition period	166	300		
Egg-to-20% OV (gen. time)	478	860		

13. Model Degree-Day Events Summary	**DDs (C)**	**DDs (F)**	
First Spring Egg-Laying	25	45	assume adults overwinter and can begin laying eggs after nominal Pre-OV period
Peak Spring Egg-Laying	58	105	
First adults G1	500	900	
Peak 1st Gen. Egg-Laying	536	964	
Peak 2nd Gen. Egg-Laying	1013	1824	
Peak 3rd Gen. Egg-Laying	1491	2683	
Peak 4th Gen. Egg-Laying	1968	3543	
Peak 5th Gen. Egg-Laying	2446	4402	
Peak 6th Gen. Egg-Laying	2923	5262	
Peak 7th Gen. Egg-Laying	3401	6121	
Peak 8th Gen. Egg-Laying	3878	6981	

14. Model Degree-Day Event Ranges Summary	Begin C	End C	Begin F	End F
OW Adults feed on nectar and find hosts	0	25	0	45
1st Spring Egg-Laying by OW Adults	25	191	45	345
1st Spring immatures (larvae, pupae)	314	528	565	951
1st Gen. Adults Egg-Laying	503	980	905	1764
1st and 2nd Gen. Adults	981	1458	1765	2624
Max. 3rd Gen. Adults; Peak 2nd Gen.	1458	1936	2625	3484
Max. 4th Gen. Adults; Peak 3rd Gen.	1936	2413	3485	4344
Max. 5th Gen. Adults	2414	2891	4345	5204
Max. 6th Gen. Adults; Peak 4th Gen.	2892	3369	5205	6064
Max. 7th Gen. Adults; Peak 5th Gen.	3369	3847	6065	6924
Max. 8th Gen. Adults	3847	4324	6925	7784
Max. 9th Gen. Adults; Peak 6th Gen.	4325	4802	7785	8644
Max. 10th Gen. Adults; Peak 7th Gen.	4803	5280	8645	9504
Max. 11th Gen. Adults; Peak 8th Gen.	5281	5758	9505	10364
Max. 12th Gen. Adults	5758	6236	10365	11224
9 to 13 or more overlapping generations	6236	6713	11225	12084

CLIMATE SUITABILITY MODEL

15. van Damme, V., N. Berkevens, R. Moerkens, E. Berckmoes, L. Wittemans, R.V.H. Casteels, L. Tirry, and P. Clercq. 2015. Overwintering potential of the invasive leafminer *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) as a pest in greenhouse tomato production in Western Europe. J. Pest Sci. 88:533-541.

- The insect's cold hardiness and OW potential was assessed by determining: (1) the supercooling point of larvae, pupae, adults; (2) the lower lethal time at 0 and 5C; (3) reproductive diapause incidence
- The study was conducted because several sites in Belgium were infested with leafminers at the start of the growing season, suggesting they had overwintered in nearby greenhouses
- Results: (1) adults were more cold hardy than larvae and pupae at both 0 and 5C with the median lower lethal time averaging 17.9 and 27.2 days, respectively
  (2) mean supercooling point was -18.2, -16.7, and -17.8C for larvea, pupae, and adults, respectively
  (3) no reproductive diapause was observed
  (4) day length affected the duration of the oviposition period - relationship varied with temperature
- Conclusions: (1) the pest is likely to successfully overwinter in commercial greenouses in Western Europe
  (2) At a constant temp of 5C at least 3 weeks are needed to kill 90% of pupae and more than 1 month to kill 90% of adults
- Notes: their values are more extreme than data collected by Kahrer et al. 2018

Exposure to 0C	Days	Weeks
Days until 50% adult mortality	17.9	2.56
Days until 90% adult mortality	30.3	4.33
Exposure to 5C		
Days until 50% adult mortality	27.2	3.89
Days until 90% adult mortality	36.3	5.19

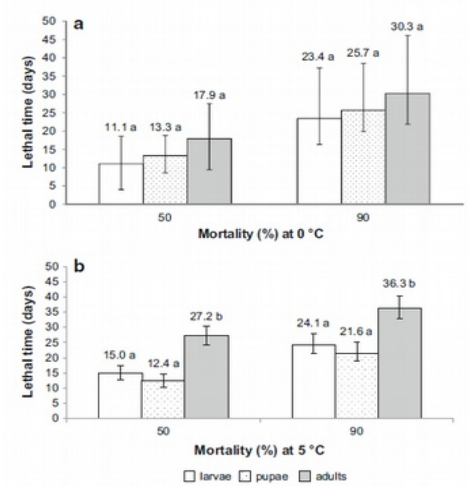


Fig. 1 Lethal time$_{50}$ and lethal time$_{90}$ (mean ± 95 % fiducial limits) at 0 (a) and 5 °C (b) for larvae, pupae, and adults of *Tuta absoluta*. Bars bearing different letters are statistically different based on non-overlapping 95 % fiducial limits

16. Kahrer, A., A. Moyses, L. Hochfellner, W. Tiefenbrunner, A. Egartner, T. Miglbauer, K. Mullner, L. Reibacher, C. Pilz, J. Votzi, and H. Scheifinger. 2018. Modelling time-varying low-temperature-induced mortality rates for puae of *Tuta absoluta* (Gelechiidae, Lepidoptera). J. Appl. Entomol. 143:1143-1153.

- Goal: establish a mathematical model for the accumulation of hourly mortalities of *T. absoluta* at variable temps
- Pupae are the most frost tolerant stage of the species; so they focused on pupae
- Subjected pupae to ~14 days of cooling at 6C in order to induce "cold adaptation"
- Calculated Lt99.99 (mortalities near 99.99%) at -10, -8, -6, -4, -2, 0, 2, 4 and 6C
- The relationship between time and mortality was tested by holding pupae at a fixed temp of -6C (mean values are in Fig. 2, below); relationship quantified w/ a 3 param Weibull function
- Results: (1) the Weibull function described 99.8% of the variation in Lt99.99 values at the various temps
  (2) the control group held at 6C had a mean mortality of 27.8% (this is lower than van Damme et al. 2015, at 90%)
  (3) no survival was possible at -17.5C

Analysis based on their data

	Max. Survival	
At 4C	Days	Weeks
	75	10.71

- To calculate a cold stress rate (THCS), following CLIMEX manual
* Entire population is likely to die after being exposed to 10.7 weeks of 4C, so stress has to accumulate to equal 1 or more across those 10.71 weeks
* This translates to a rate of 0.09 (1 week/10.71 weeks)
- However using this threshold and rate (even when rate = 0.045) excluded it even from much of Mediterranean coastline (where many records are)
- CLIMEX assumes that cold stress occurrs from starvation; whereas this experiment was measuring death by cold exposure
- After calibrating THCS based on field population records for Europe, settled on value of 0.001

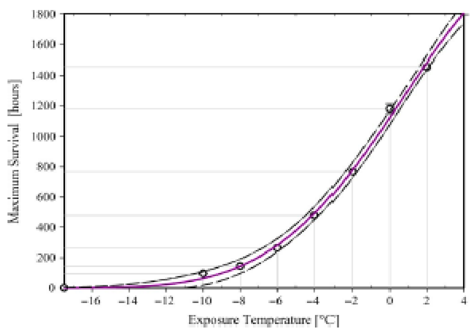


FIGURE 1 Maximum temporal survival ($Lt_{99.99}$) of cold adapted young pupae of *Tuta absoluta* at various low temperatures. The data were fitted by a Weibull function presented as Equation 1. The dashed line shows the 95% confidence band

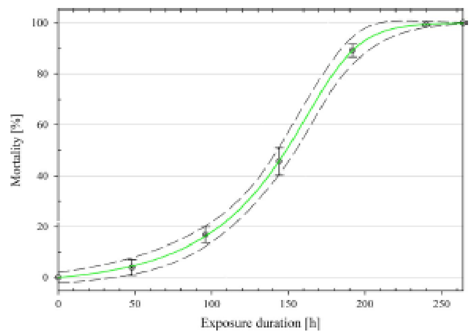


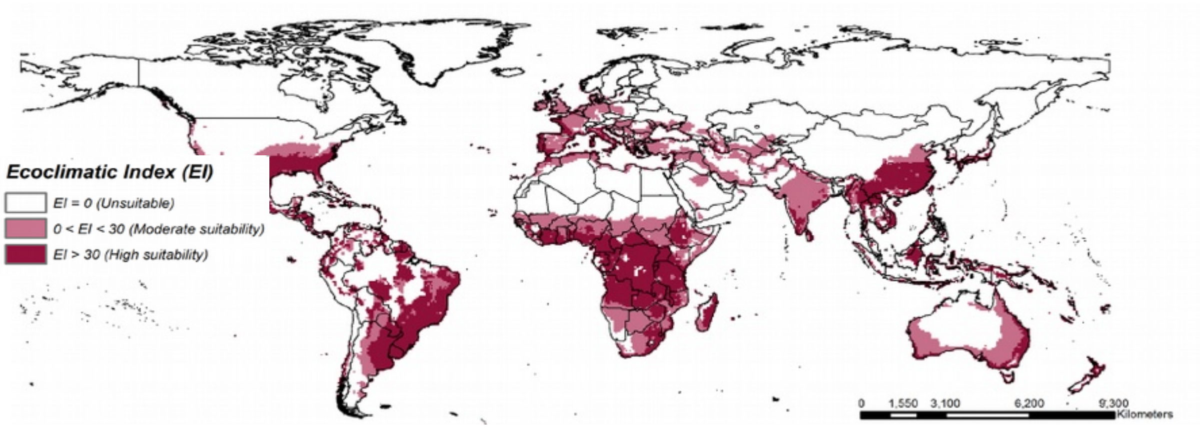
FIGURE 2 Accumulated mortalities of cold adapted pupae of *Tuta absoluta* exposed to a constant frost of −6°C. The dashed line shows the 95% confidence band. The fitted curve is described by a sigmoidal function (Equation 2)

17. Santana, P., L. Kumar, R.S. da Silva, and M.C. Picanço. 2019. Global geographic distribution of *Tuta absoluta* as affected by climate change. J. Pest Sci. 92:1373-1385.

- Optimized CLIMEX parameters from three previous CLIMEX studies on species (Desneux et al. 2010; Tonnang et al. 2015; Xian et al. 2017)
- In the calibration step, the intial model was based on areas where it is known to be absent in NW Brazil and present in central regions
- They applied a hot-wet stress parameter because this resulted in more accurate predictions
- In the validation step, output was compared to known distributions in Brazil by quantifying percentage of points that fell in suitable areas
- Additionally, they visualized output against known distributions in other parts of the world

Issues with this study

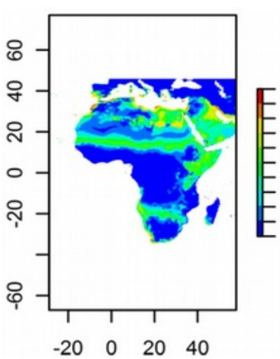
- Their cold stress param (TTCS = 7) appears to have no basis. They state it is based off of Martins et al. (2016) data, but these authors did not measure survival at temps lower than 17C
- Overall in considering these errors and omissions, it was determined that cold stress params need to be adjusted (see also van Damme et al. 2015; Kahrer et al. 2018)



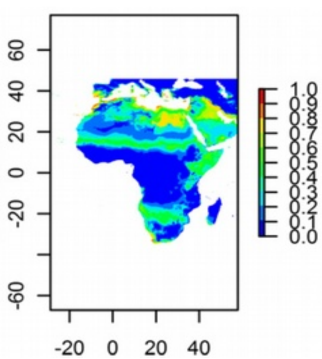
18. Biber-Freudenberger, L., J. Ziemacki, H. Tonnang, and C. Borgemeister. 2016. Future risks of pest species under changing climate conditions. PLoS ONE 11:1-17. 10.1371/journal.pone.0153237

- Used Maxent (a correlative niche modeling program) to predict current and future climate suitability for *T. absoluta* and 2 other insect pests in Africa under
- BIO12 (annual precip) and BIO6 (min temp of coldest month) were the most important variables in the model
- Map results for *T. absoluta* are shown below (froms Fig. 2)
- They used very few locality records to train the model (see below, right), which likely explains why the predicted distribution in Africa is so different than CLIMEX models

Current climate



Future (2041-2060) climate



Localities used

19. Desneux, N., E. Wajnberg, K.A.G. Wyckhuys, G. Burgio et al. 2010. Biological invasion of European tomato crops by *Tuta absoluta* ecology, geographic expansion and prospects for biological control. J. Pest. Sci 83:197-215.

- An earlier CLIMEX model for the species, but their chill stress threshold better predicts known field distribution of the species in the European Mediterranean than other 2 CLIMEX studies
- They used TTCS = 3 and THCS = -0.001
- However using Santana et al's (2019) parameters with their TTCS/THCS values predicts high suitability throughout much of Europe, where the species is only known to be established in greenhouses (below right)

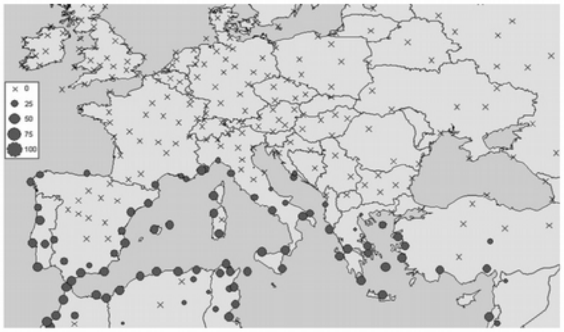
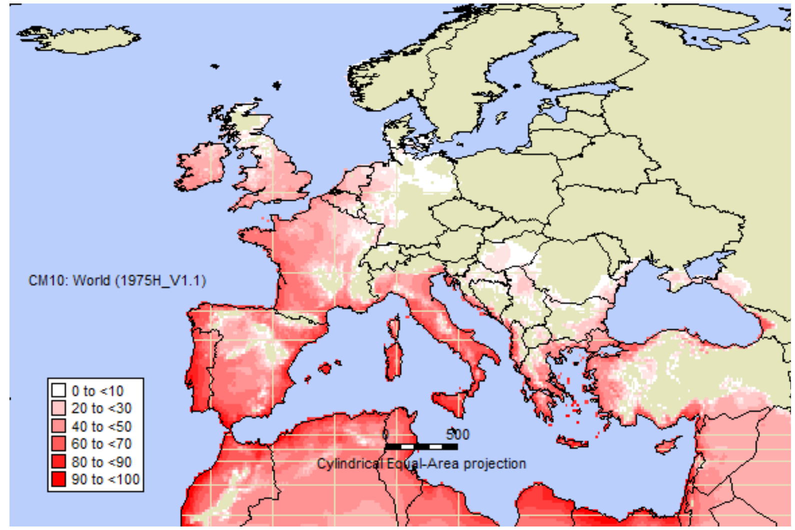


Fig. 2 The predicted distribution Ecoclimatic Index (EI) of *Tuta absoluta* in Europe and North African countries. The *dots* represent EI values with increasing dots' size indicating higher EI values. The higher the EI value, the more suitable the climate at that location (EI ~ 10: species could survive, 30: very favourable, Sutherst et al. 2007). Biological parameters of *T. absoluta* used in the model are from Marcano (1995), Betancourt et al. (1996) and Barrientos et al. (1998). The potential distribution of *T. absosulta* is based both on its establishment in Europe (in the early 2008) and its presence in South America. Information from South America were included (more than 150 locations from Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay and Venezuela were used during the parameter fitting process). Parameters used in Climex model: moisture index: SM0 = 0.1, SM1 = 0.4, SM2 = 0.7, SM3 = 2; temperature index: DV0 = 8, DV1 = 20, DV2 = 25, DV3 = 35; cold Stress: TTCS = 3, THCS = −0.001, DTCS = 15, DHCS = −0.001, TTCSA = 0, THCSA = 0; heat Stress: TTHS = 35, THHS = 0.0015, DTHS = 0, DHHS = 0; dry Stress: SMDS = 0.1, HDS = −0.01; wet Stress: SMWS = 2, HWS = 0.002; day degree accumulation above DVO: DVO = 8, DV3 = 35, MTS = 7; day degree accumulation above DVCS: DVCS = 8, DV4 = 100; day degree accumulation above DVHS: DVHS = 35; degree-days per generation: PDD = 460



20. Han, P., Hayram, Y., Shaltiel-Harpaz, L., Ensanli, T. et al. 2018. *Tuta absoluta* continues to disperse in Asia: damage, ongoing management and future challenges. J. Pest Sci. 92:1317-1327.

- The study reviews the spread and status of the species in Asia, but also presents their own CLIMEX model
- Their CLIMEX model appears to overpredict the species' distribution in South America compared to Santana et al. 2018, who validated their South America model using records
- Their TTCS and THCS values came from previous studies (Desneux et al. 2010; Source 19, above); so it appears they overlaid a blue polygon on top of the suitable areas in northern Europe

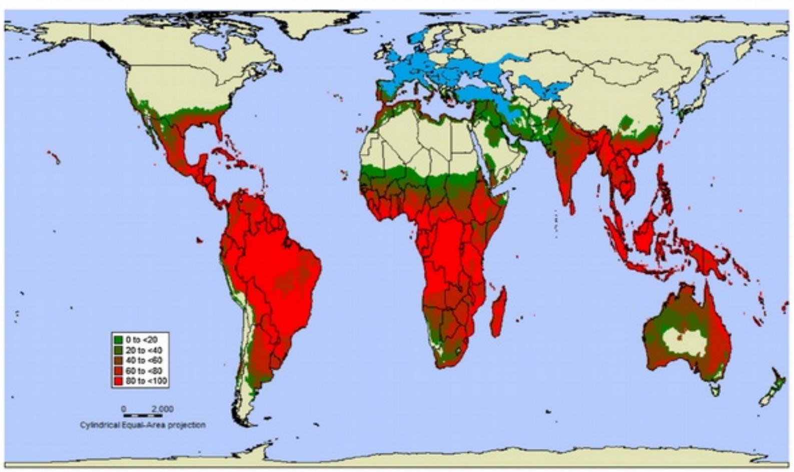


Fig. 1 Predicted distribution on Eco-climatic Index (EI) of *Tuta absoluta* throughout the world. EI values indicate the suitability of this pest (i.e. green and red regions). The blue are the invaded areas by this pest but outside of suitable areas for the moth. The higher the EI values are the more suitable climate under which *T. absoluta* could survive (Ei = 0: cannot survive, EI ~ 10: species could survive, 30: very favourable, Sutherst et al. 2007). Parameters used in CLIMEX model: moisture index: temperature index: DV0 = 8, DV1 = 20, DV2 = 30, DV3 = 42; cold Stress: TTCS = 3, THCS = −0.001, DTCS = 15, DHCS = −0.001, TTCSA = 0, THCSA = 0; heat Stress: TTHS = 42, THHS = 0.0015, DTHS = 0, DHHS = 0; dry Stress: SMDS = 0.1, HDS = −0.01; wet Stress: SMWS = 2, HWS = 0.002; day degree accumulation above DVO: DVO = 8, DV3 = 42, MTS = 7; day degree accumulation above DVCS: DVCS = 8, DV4 = 100; day degree accumulation above DVHS: DVHS = 35; degree-days per generation: PDD = 460. (Color figure online)

21. GBIF.org, search for *Tuta absoluta* records; accessed 1/13/20

Plus additional field population records collected from the literature

- Visualized records for Europe in an effort to refine an appropriate CLIMEX cold stress threshold
- Localities in Belgium are from individuals that overwintered in greenhouses - not populations established outdoors year round
- The data download provided no info on whether records were from greenhouses or field, so could not use for CLIMEX model calibration
- Appears that localities are only in southern Europe along Mediterranean coast; this is supported by the Maxent model of Biber-Freudenberger et al. (2016)

Known field populations of *T. absoluta* in Europe / Turkey / Iran

- Additional records may further help fit a CLIMEX model; however, the ones here support the assertion that the species is primarily limited to warm/humid areas along the Mediterranean coast (in Europe/Turkey)

Locality	Country	Lat	Long	Source	
Grosseto Province	Italy	42.76	11.11	Balzan and Moonen (2012) Bulletin OEPP/EPPO Bulletin 42:217-225	
NE site 1	Spain	42.04	3.18	Gabarra et al. (2014) BioControl 59:45-54	
NE site 2	Spain	40.67	0.58	Gabarra et al. (2014) BioControl 59:45-54	
NE site 3	Spain	41.63	0.60	Gabarra et al. (2014) BioControl 59:45-54	
Central site 1	Spain	40.30	0.27	Gabarra et al. (2014) BioControl 59:45-54	
Central site 2	Spain	39.39	-0.52	Gabarra et al. (2014) BioControl 59:45-54	
SE site 1	Spain	36.83	-2.55	Gabarra et al. (2014) BioControl 59:45-54	
SE site 2	Spain	36.84	-2.44	Gabarra et al. (2014) BioControl 59:45-54	
SE site 3	Spain	36.74	-2.13	Gabarra et al. (2014) BioControl 59:45-54	
Bologna	Italy	44.50	11.26	iNaturalist research grade	
Belvedere	Italy	42.08	12.54	iNaturalist research grade	
Macchione	Italy	41.51	13.34	iNaturalist research grade	
Yenişehir, Bursa	Turkey	40.26	29.65	Kovanci and Pehlevan (2013) 24th Intl Sci-Expert Conference of Agriculture and Food Industry – Sarajevo 2013	
Izmir Province	Turkey	38.32	26.81	Kılıç (2010) Phytoparasitica 38:243-244	
Urmia city	Iran	38.04	45.07	Baniameri and Cheraghani (2012)	
Shiraz, Fars Prov.	Iran	25.59	52.58	Pezhman and Saeidi (2018) Not Sci Biol 10:475-484	
Khatlon region	Tajikstan	37.82	69.12	Saidov et al. (2018) Fla Entomol 101:147-149 (field and greenhouse)	
Dist of Repub Subordin	Tajikstan	38.71	69.28	Saidov et al. (2018) Fla Entomol 101:147-149 (field and greenhouse)	
Hula Valley	Israel	33.25	35.58	Shaltiel-Harpaz et al. (2015) J Econ Entomol 109:120-131	
Beit Shean Valley	Israel	32.50	35.50	Shaltiel-Harpaz et al. (2015) J Econ Entomol 109:120-131	
Bismil, Diyarbakır	Turkey	37.85	40.67	Bayram et al. (2014) Bitki Koruma Bulteni 54:343-354	Seems to be central - OW in greenhouses?
Ergani Co., Diyarbakir	Turkey	38.27	39.76	Bayram et al. (2014) Bitki Koruma Bulteni 54:343-354	Seems to be central - OW in greenhouses?
Preveza	Greece	38.97	20.75	Roditakis and Papachristos (2010) Bulletin OEPP/EPPO 40:163-166	Unclear if greenhouse/field (both situations reported)
Axaia	Greece	38.15	21.54	Roditakis and Papachristos (2010) Bulletin OEPP/EPPO 40:163-166	Unclear if greenhouse/field (both situations reported)
Trifilia	Greece	37.23	21.69	Roditakis and Papachristos (2010) Bulletin OEPP/EPPO 40:163-166	Unclear if greenhouse/field (both situations reported)
Stajkovce	Serbia	42.99	22.06	Toševski et al. (2011) Pestic Phytomed (Belgrade) 26:197-204	Authors claim the population is established here

22. CLIMEX model generated for this study

Parameters used in final CLIMEX model (modified from Santana et al. 2019)

Moisture Index

SM0	SM1	SM2	SM3
0.1	0.4	1.6	2

Temperature Index

DV0	DV1	DV2	DV3
7	14	30	34.6

Cold Stress (new)

TTCS	THCS	DTCS	DHCS	TTCSA	THCSA
4	-0.001	0	0	0	0

Heat Stress

TTHS	THHS	DTHS	DHHS
34.6	0.0001	0	0

Dry Stress

SMDS	HDS
0.1	-0.01

Wet Stress

SMWS	HWS
2	0.015

Hot-Wet Stress

TTHW	MTHW	PHW
30	0.6	0.003

Day-degree accumulation above DV0

DV0	DV3	MTS
7	34.6	7

Day-degree accumulation above DVCS

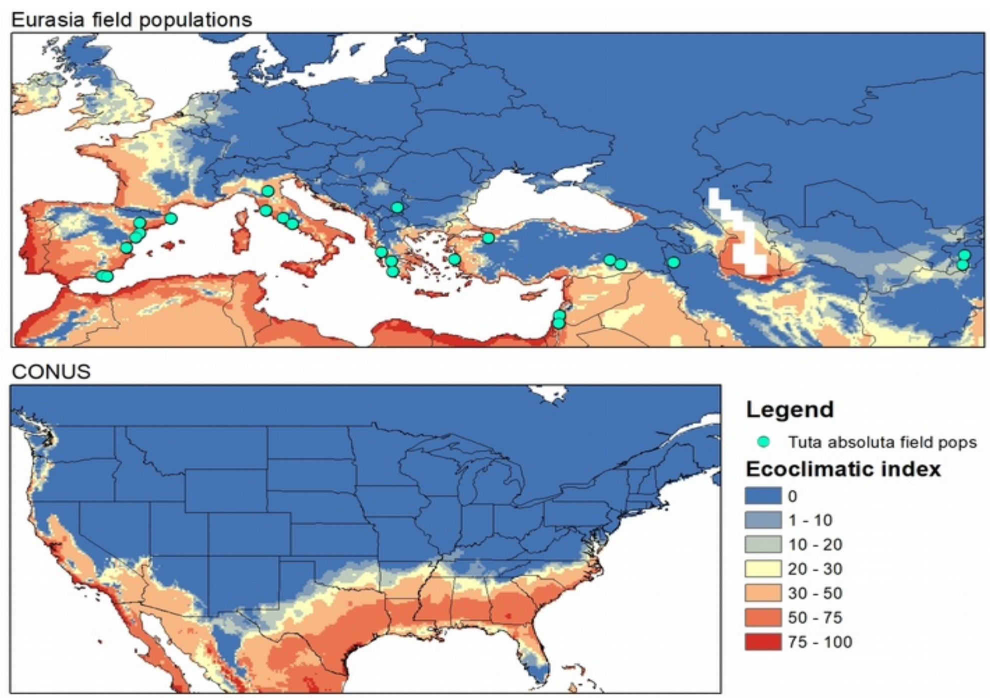
DVCS	*DV4	MTS
10	100	7

Day-degree accumulation above DVHS

DVHS	*DV4	MTS
40	100	7

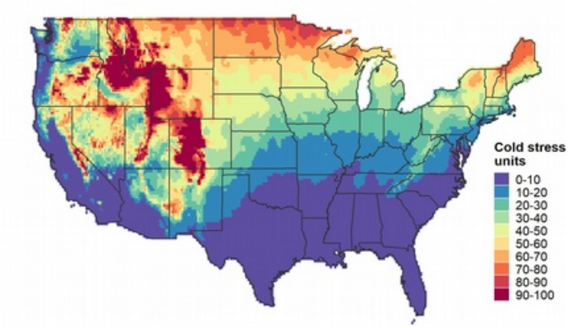
Degree-days per Generation

PDD
460

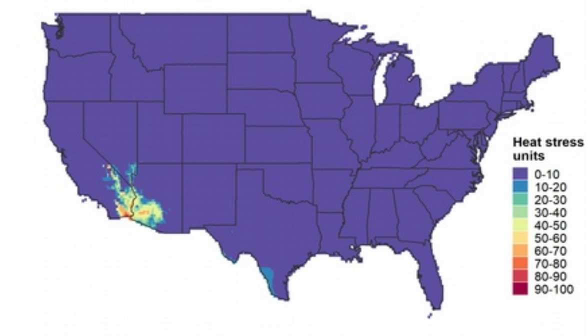


Figures for CONUS generated using these CLIMEX parameters
- Stress unit values have been scaled from 0 to 100

Cold Stress

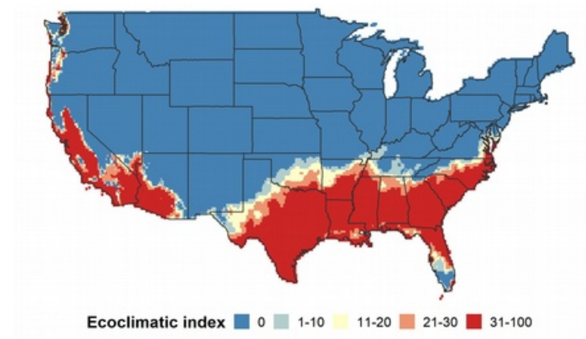


Heat Stress



Hot-Wet Stress

EI



23. Final review of parameters

Thresholds, degree-days and events used in Tomato leafminer model:

Parameter abbr.	Description	degF	degC	DDF	DDC
eggLDT	egg lower dev threshold	46.0	7.8	-	-
eggUDT	egg upper dev threshold	95.0	35.0	-	-
larvaeLDT	larvae lower dev threshold	46.0	7.8	-	-
larvaeUDT	larvae upper dev threshold	95.0	35.0	-	-
pupaeLDT	pupae lower dev threshold	46.0	7.8	-	-
pupaeUDT	pupae upper dev threshold	95.0	35.0	-	-
adultLDT	adult lower develpmental threshold	46.0	7.8	-	-
adultUDT	adult upper dev threshold	95.0	35.0	-	-
eggDD	duration of egg stage in DDs	-	-	135	75
larvaeDD	duration of larvae stage in DDs	-	-	385	214
pupaeDD	duration of pupae stage in DDs	-	-	248	138
adultDD	duration of adult stage in DDs	-	-	150	83
Gen TimeDD	duration of generations in Dds	-	-	860	478
OWadultDD	DDs until OWadults emerge	-	-	45	25
eggEventDD	DDs into egg stage when hatching begins	-	-	135	75
larvaeEventDD	DDs into larvae stage when mid-larval occurs	-	-	193	107
pupaeEventDD	DDs at end of pupae stage - first adult emergence	-	-	248	138
adultEventDD	DDs into adult stage when 1st oviposition occurs	-	-	45	25

Parameter abbr.	Description	degF	degC	DDF	DDC
chillstress_threshold	chill stress threshold	35.6	2.0	-	-
chillstress_units_max1	chill degree day limit when most individuals die	-	-	540	300
chillstress_units_max2	chill degree day limit when all individuals die	-	-	927	515
heatstress_threshold	heat stress threshold	98.6	37.0	-	-
heatstress_units_max1	heat stress degree day limit when most individuals die	-	-	1080	600
heatstress_units_max2	heat stress degree day limit when all individuals die	-	-	1710	950
distro_mean	average DDs to emergence	-	-	45	25
distro_var	variation in DDs to emergence	-	-	360	200
xdist1	minimum DDs (°C) to emergence	-	-	2	1
xdist2	maximum DDs (°C) to emergence	-	-	108	60
distro_shape	shape of the distribution	-	-	normal	