Phenology/Degree-Day Model Analysis – Vers. 1.1, Dec. 5, 2019

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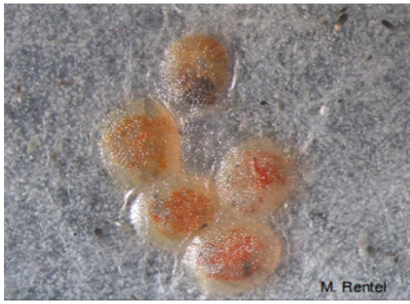
False Codling Moth ***Thaumatotibia leucotreta*** **(Meyrick) [Lepidoptera: Tortricidae]**



Native to: sub-Saharan Africa; also established in Israel

Hosts: Citrus, corn, cotton, macadamia, avocado, stone fruits, pepper, tomato

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

- We propose a compromise lower temperature threshold of 11.7C or 53F
- Studies by Daiber (below) suggested a low threshold of ca. 11.7°C for eggs, 11.9 to 12.5°C for larvae instars, 11.9°C for pupae, and 12.2°C for adults
- The pupal stage has the longest development of the stages, considered to be the primary OW stage producing first adults in spring

Thresholds, degree-days and events used in false codling moth model (DDRP platform):

Parameter abbr.	Description	degC	degF	DDC	DDF
eggLDT	egg lower dev threshold	11.7	53.0	-	-
eggUDT	egg upper dev threshold	38.0	100.4	-	-
larvaeLDT	larvae lower dev threshold	11.7	53.0	-	-
larvaeUDT	larvae upper dev threshold	38	100.4	-	-
pupaeLDT	pupae lower dev threshold	11.7	53.0	-	-
pupaeUDT	pupae upper dev threshold	38	100.4	-	-
adultLDT	adult lower develpmental threshold	11.7	53.0	-	-
adultUDT	adult upper dev threshold	38	100.4	-	-
eggDD	duration of egg stage in DDs	-	-	71	128
larvaeDD	duration of larvae stage in DDs	-	-	155	279
pupaeDD	duration of pupae stage in DDs	-	-	175	315
adultDD	duration of adult stage PreOV plus ca. 50% OV in DDs	-	-	83	150
egg_to_adult_DD	generation time egg to first adult			400	720
egg_to_50%OV_DD	generation time egg to 50% OV in Dds			484	871
OWpupaeDD	DDs until OWpupae complete devel and emerge as adults in spring			220	396
eggEventDD	DDs into egg stage when hatching begins	-	-	71	128
larvaeEventDD	DDs into larvae stage when mid-larval occurs	-	-	77	139
pupaeEventDD	DDs until first adults emerge	-	-	145	261
adultEventDD	DDs into adult stage when 1st oviposition occurs	-	-	17	31
chillstress_threshold	chill stress threshold	-1	30.2	-	-
chillstress_units_max1	chill degree day limit when most individuals die			5	9
chillstress_units_max2	chill degree day limit when all individuals die			125	225
heatstress_threshold	heat stress threshold	40	104.0	-	-
heatstress_units_max1	heat stress degree day limit when most individuals die			75	135
heatstress_units_max2	heat stress degree day limit when all individuals die			150	270
distro_mean	average DDs to emergence			220	396
distro_var	variation in DDs to emergence			500	900
xdist1	minimum DDs (°C) to emergence			140	252
xdist2	maaximum DDs (°C) to emergence			280	504
distro_shape	shape of the distribution			normal	

Thresholds, degree-days and events used in false codling moth model (USPEST.ORG/DD/MODEL platform):

Model species/general links:	https://www.inhs.illinois.edu/files/7513/4013/2690/tleucotretapra.pdf				
Type:	Invasive insect				
Model source/other links:	IPPC synthesis of Daiber 1979, others				
Calculation method:	Single Sine	**degC**	**degF**		
Lower threshold:		11.7	53.0	-	-
Upper threshold:		38	100.4	-	-
Basis for starting date:	In S. Africa no diapause but most abundant OW stage is pupae, plus first reported flights early March (N. Hemis. Equiv.)				
Starting/Biofix date:	Jan 01				
Model validation status:	Needs field validation data; assuming overwintering mainly larval and pupal stages				
Region of known use:	Constructed for use in USA for invasive species monitoring programs				
		DDC	**DDF**		
Earliest first moth emergence		160	288		
Peak flight OW Gen.		220	396		
Peak larvae 1st Gen.		368	663		
Peak flight 1st Gen.		704	1267		
Peak larvae 2nd Gen.		852	1534		
Peak flight 2nd Gen.		1188	2138		
Peak larvae 3rd Gen.		1336	2405		
Peak flight 3rd Gen.		1672	3009		
Peak larvae 4th Gen.		1820	3276		
Peak flight 4th flight		2156	3880		
Peak larvae 5th Gen.		2304	4147		
Peak flight 5th Gen.		2639	4751		
Peak larvae 6th Gen.		2788	5018		
Peak flight 6th Gen.		3123	5622		

Source 1. Daiber, C.C. 1979. A study of the biology of the false codling moth [*Cryptophlebia leucotreta* (Meyr.): the egg. Phytophylactica. 11:129-132.

- Raised eggs at constant temperatures of 15, 20, and 25C
- Calculated an eggLDT = 11.7C
- Eggs stopped hatching at an avg. temperature of 10.6C and lower
- High mortality of occurred when eggs exposed to 13C and relative humidty of 30%
- Eggs required 69.3 DDs above the LDT to complete development
- The rate of development was a linear function of temperature: $y = 0.014426x - 0.172067$

degC	days to 50% egg hatch
15	19.5±2
20	9.8±0.1
25	5.1±0.04

Source 2. Daiber, C.C. 1979. A study of the biology of the false codling moth [*Cryptophlebia leucotreta* (Meyr.): the larva. Phytophylactica. 11:141-144.

- The larva pass through 5 larval instars, of which the first must find a suitable host fruit
- There was a close linear relationship between the reciprocal of the duration of the larval stage at three constant temperatures (15, 20 and 25C)
- Food quality greatly influenced the surival of larvae and the duration of the larval stage
- The LDT for different instars ranged from 11.9C to 12.5C
- At a LDT of 11.6C the DDs for larval development was 156
- The calculated LDTs are similar to those observed for the egg stage (Source #1)
- They indicated that development is initiated at a relatively high temperature, and larval development is very slow at a few degrees above the LDT (winter conditions) but rapid between 20 and 30C (summer conditions)

degC	avg. duration of larval stage
15	45.6±0.2
20	18.8±0.1
25	11.6±0.1

Source 3. Daiber, C.C. 1980. A study of the biology of the false codling moth *Cryptophlebia leucotreta* (Meyr.): the cocoon. Phytophylactica. 11, 151-157.

- The cocoon is made by the 5th instar larva, now prepupa, then moults into the pupa
- Similar to sources 1 & 2, raised cocoon stage at 15, 20, and 25C and found close inverse relationship between temperature and duration of stage
- Mortality of prepupae and pupae was high at avg temps of 10.5C and lower
- Number of adults emerging from cocoons greatly reduced when cocoons were exposed to low relative humidity
- Calculated a lower threshold of 11.9C

degC	avg. duration of larval stage
15	50.7±0.7
20	22.3±0.2
25	12.9±0.2

Source 4. Daiber, C.C. 1980. A study of the biology of the false codling moth *Cryptophlebia leucotreta* (Meyr.): the adult and generations during the year. Phytophylactica. 12:187-193.

- The life span of males and females and egg laying were observed at constant temperatures of 10, 15, 20, and 25C
- Both sexes lived longest at 15C while most eggs were laid at 25C
- Very few eggs were laid at 10C
- The duration of a generation was highly temperature dependent with up to five generations per year in Pretoria, South Africa; 6 at Hort Res Inst Roodeplast, SA
- On average male moths had shorter life spans than female moths
- Calculated a LDT of 14.4C for the preOV period; and 12.2C for the period when 50% of eggs were laid
- At avg ambient temps of 12.3 to 24C, the avg preOV period varied from 1 and 2.2 days
- Data from Table 1 (PreOV period in days) are below
- PreOV and 50% eggs laid data point for 10C were removed (see below) because the sample size was low (10-12 pairs of moths), and only 1 female laid eggs (N=6 eggs). It doesn't make sense that number of days to oviposit and for 50% egg hatch would be lower at 15C than at 10C.

Data from Table 1

degC	PreOV period	Age of females (days) having laid 50% of eggs	
10	22	23	these data were removed in solving for a common threshold
15	13.5±1.4	26.5±2.6	
20	3.2±0.5	11.1±1.2	
25	1.1±0.1	6.0±0.5	

Data presented by Venette et al. 2003

Dev threshold	Degree Days	Description	Source
8	232.0	Male life span	Table 1 - this study
8.1	229.8	Male life span	(from Daiber 1975; Table 5)
9.5	243.5	Female life span	Table 1 - this study

Data from embedded Table page 192

Gen

Gen	DDs>11.7
1.0	378.0
2.0	432.0
3.0	367.0
4.0	364.0
5.0	344.6
6.0	364.7
7.0	44.0
average	327.8

Source 5. Daiber, K.C. 1989. The false codling moth, Cryptophlebia leucotreta (Meyr.) (Lepidoptera: Tortricidae), in southern Africa. Zeitschrift für Pflanzenkrankheiten und Pflanzenschutz 96: 71-80.

- Under lab conditions, the pupal stage lasts between 2-33 days, depending on the temperature
- Pupae are sensitive to cold temperatures and heavy rainfall

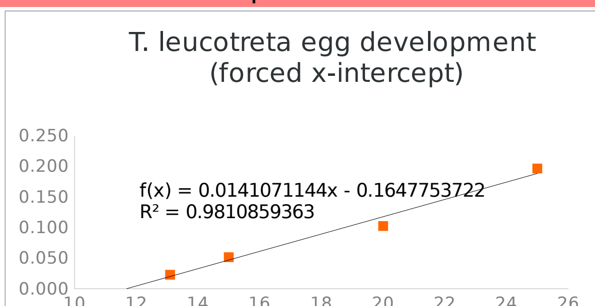
Re-interpret temperature vs. development rate data to solve for best overall common threshold and corresponding developmental DDs:

Yellow background: point added to force x-intercept
Salmon background: most relevant results
Red background: values are outliers - removed

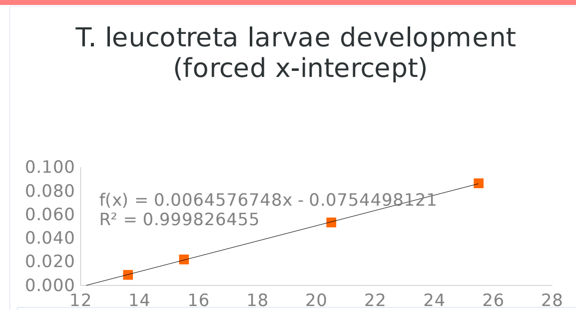
Days Development

Temp C	Egg	Larvae	Pupa	PreOV	50% Eggs L	1st OV to 50% Eggs Laid	EggToAdult
	44	112	125	28	110	75.0	281
10				22	23.0		
15	19.5	45.6	50.7	13.5	26.5	13.0	116
20	9.8	18.8	22.3	3.2	11.1	7.9	51
25	5.1	11.6	12.9	1.1	6.0	4.9	30

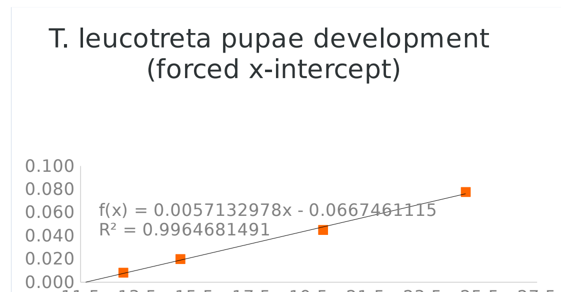
	Egg		**Larvae**		**Pupae**		**PreOV**		**PreOV to 50% OV**		**1st OV to 50% OV**		**Egg to Adult**	
	Temp C	1/days	Temp C	1/days	Temp C	1/days	Temp C	1/days	Temp C	1/days	Temp C	1/days	Temp C	1/days
	13	0.023	13	0.009	13	0.008	10	0.036	12	0.009	14.0	0.013	13	0.004
													15	0.009
	15	0.051	15	0.022	15	0.020	15	0.074	15	0.038	15	0.077	20	0.020
	20	0.102	20	0.053	20	0.045	20	0.313	20	0.090	20	0.127	25	0.034
	25	0.196	25	0.086	25	0.078	25	0.909	25	0.167	25	0.204		
	slope:	0.014	slope:	0.006	slope:	0.006	slope:	0.057	slope:	0.012	slope:	0.015	slope:	0.003
	intercept:	-0.165	intercept:	-0.075	intercept:	-0.067	intercept:	-0.668	intercept:	-0.141	intercept:	-0.180	intercept:	-0.029
	R-sq:	0.981	R-sq:	1.000	R-sq:	0.996	R-sq:	0.838	R-sq:	0.988	R-sq:	0.940	R-sq:	0.997
Tlow (°C) =	-a/b	11.7		11.7		11.7		11.7		11.7		11.7	**-a/b**	11.7
Tlow (°F) =	-a/b	53.0		53.0		53.0		53.0		53.0		53.0	**-a/b**	53.1
DDCs devel =	1/slope	71		155		175		17		83		65	**1/slope**	399.8
DDFs devel =	1/slope	128		279		315		31		150		117	**1/slope**	719.6



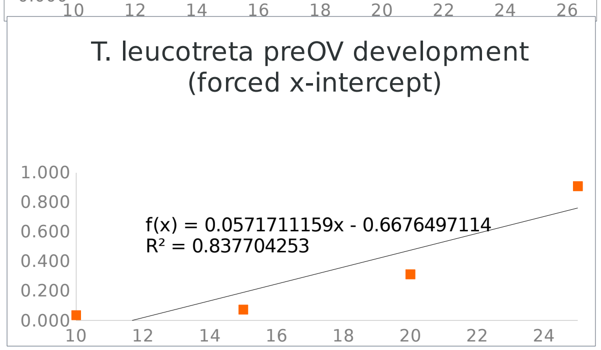
T. leucotreta egg development (forced x-intercept)



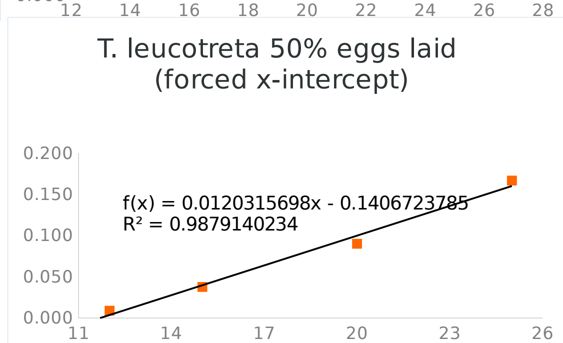
T. leucotreta larvae development (forced x-intercept)



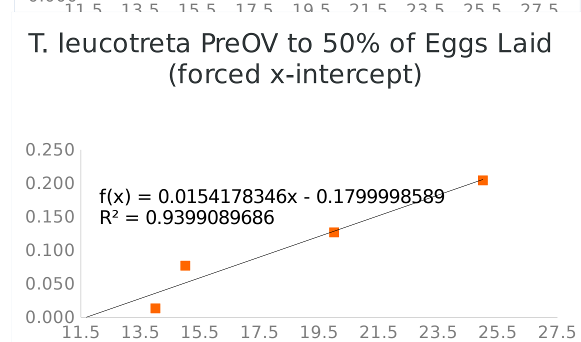
T. leucotreta pupae development (forced x-intercept)



T. leucotreta preOV development (forced x-intercept)



T. leucotreta 50% eggs laid (forced x-intercept)



T. leucotreta PreOV to 50% of Eggs Laid (forced x-intercept)

Source 6. NAPPFAST. 2003. Pest assessment: False codling moth, Cryptophlebia leucotreta (Meyrick) (Lepidoptera: Tortricidae).
- very few eggs laid at 10C (Daiber 1980) pre-OV 27DD (12C).
- Peak OV within 3 days after emergence
- 50% eggs laid 1st 1/3 of repro period. Survival reduced below 10C.
- Temps below 10ºC reduces survival or development of several life stages
- Eggs/other stages killed below 1C
- Omnivourous - assume host plants avail everywhere/not limiting.
- Assumed an upper developmental threshold of 40C, and lower developmental threshold of 12C
- No OW stage but pupae selected as longest stage

Source 7. Stotter, R.L. and J.S. Terblanche. 2009. Low-temperature tolerance of false codling moth *Thaumatotibia leucotreta* (Meyrick) (Lepidoptera: Tortricidae) in South Africa. Journal of Thermal Biology. 34:320-325.
- Probability of adult survival of 50% of the population at -4.5C was 2 h
- Probability of adult survival of 50% of the population at -1C was 10 h
- Limited evidence for rapid cold hardening, which suggests that it has limited capacity to adjust its thermal tolerance over short, daily timescales
- Used 40C as the high temp treatment
- High temp pre-treatments had no significant effect on low-temperature survival
- In an orchard in South Africa in 2008-2009, -1C was the temp estimated to be lethal for 50% of the population when exposed for 10h

Source 8. Boardman, L., T.G. Grout, and J.S. Terblanche. 2012. False codling moth *Thaumatotibia leuctoreta* (Lepidoptera, Tortricidae) larvae are chill-susceptible. Insect Science. 19:315-328.
- Larvae have mean critical thermal minima (lower limits of activity) of 6.7C which was influenced by feeding status
- Temperature at which 50% of the larval population survives is -11.5C after 2 hr exposure
- Supercooling point was affected by fasting and relative humidity
- Cooling reates did not affect the supercooling point which suggests limited phenotypic plasticity of this trait during the larval period
- Conclusion: larvae are chill-susceptible and die upon freezing
- Fig. 1 below shows ULT$_{50}$ and LDTs estimated from this study and others

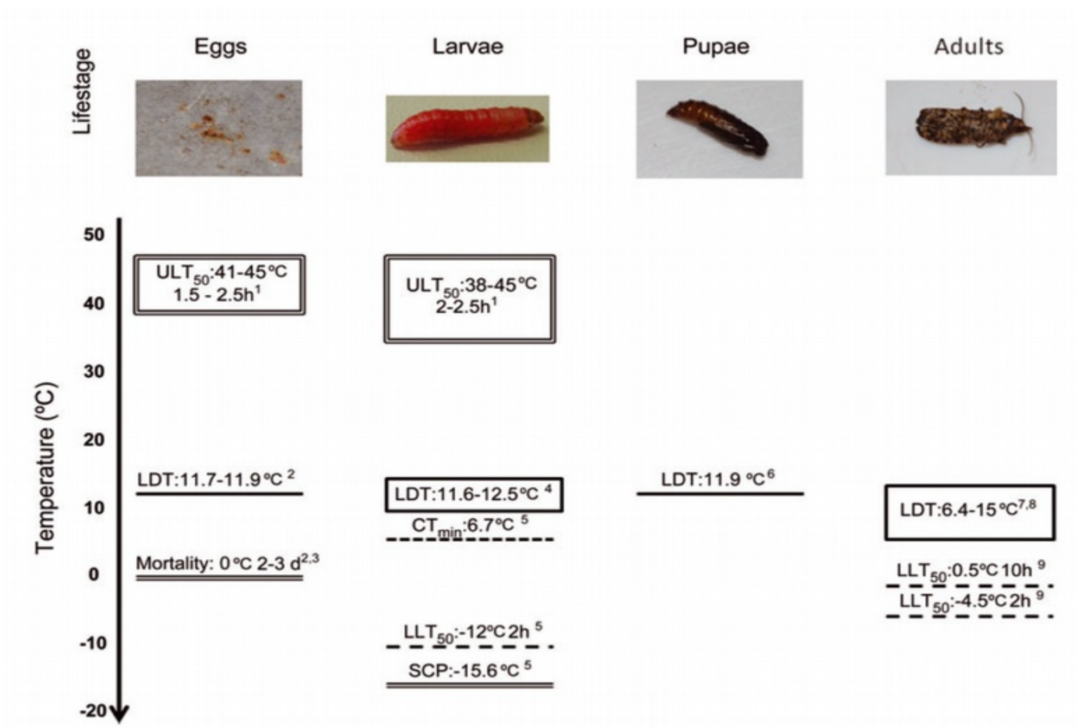


Fig. 1 Temperature tolerance of *T. leucotreta* for each of the life-stages taken from published studies. Gaps in information occur where the figure is left blank. Sources are: [1]Johnson and Neven, 2010; [2]Daiber, 1979a; [3]Blomefield, 1978; [4]Daiber, 1979b; [5]This study; [6]Daiber, 1979c; [7]Daiber, 1975; [8]Daiber, 1980; [9]Stotter and Terblanche, 2009. ULT$_{50}$, upper lethal temperature (that results in 50% mortality); LLT$_{50}$, lower lethal temperature (that results in 50% mortality); LDT, lower developmental threshold; CT$_{min}$, critical thermal minima; SCP, supercooling point.

Source 9. Johnson, S.A. and L.G. Neven. 2010. Potential of heated controlled atmosphere postharvest treatments for the control of *Thaumatotiba leucotreata* (Lepitoptera: Tortricidae). J. Econ. Entomol. 103(2): 265-271.

- see Fig. 1 of Source #8, above
- Temperature at which 50% of the egg population survives is 41-45C after 1.5-2.5 hr exposure
- Temperature at which 50% of the larval population survives is 38-45C after 2-2.5 hr exposure

Source 10. Terblanche, J.S., Z. de Jager, L. Boardman, and P. Addison. 2014. Physiological traits suggest limited diapause response in false codling moth, *Thaumatotibia leucotreta* (Lepitdoptera: Tortricidae). J. Appl. Entomol. 138:683-691.

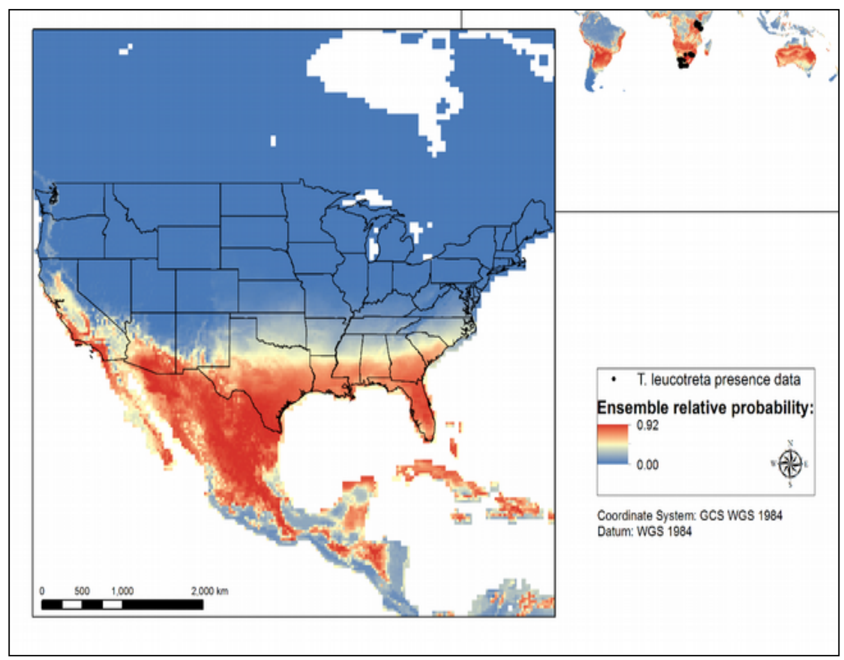
- Subjected larvae to cooling and shortening day length over a period of 14 days (Diapuse treatment group) relative to a similar-aged control group
- Tested if physiological traits and body condition varied in a direction that was relfective of diapause induction
- Did not find significant differences between groups, suggesting that the species does not undergo diapause

Source 11. Terblanche, J.S. K.A. Mitchell, W. Uys, C. Short, L. Boardman. 2017. Thermal limits to survival and activity in two life stages of false codling moth *Thaumatotibia leucotreta* (Lepidoptera, Tortricidae). Physiological Entomology. 42:379-388.

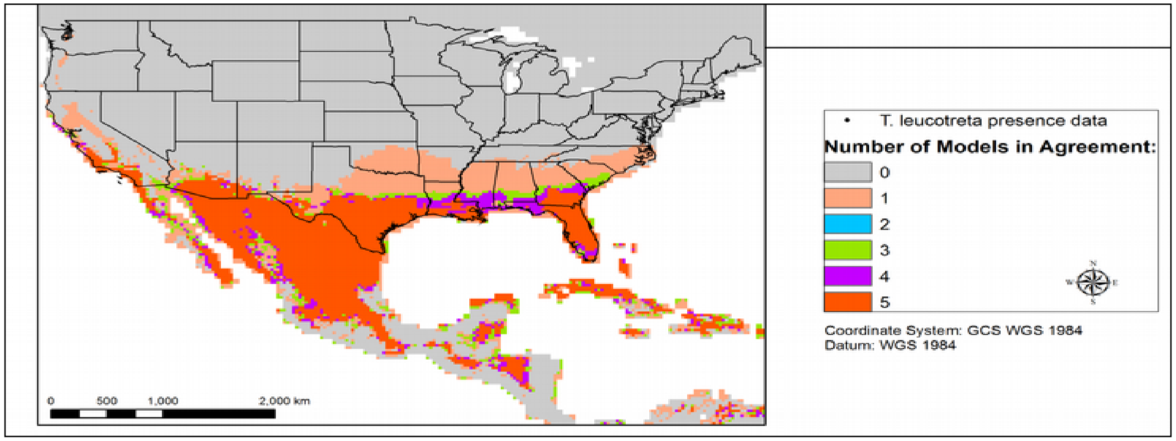
- Measured thermal tolerance (CTmax and CTmin), upper and lower lethal temperatures, and plasticity in larvae and adults
- Larvae survived across a broader range of temperatures than adults, and had more phenotypic plasticity
- But adults remained active across a broader range of temperatures
- CTmin for larvae ranged from ~6-10C depending on ramping rate, and ~2.5C for adults regardless of ramping rate
- CTmax for larvae ranged from ~42-47C depending on ramping rate, and ~42C for adults regardless of ramping rate
- High temps: Survival of adults dropped to 0% between 40 and 44C (so 40C was lethal)
- High temps: Survival of larvae dropped to 0% between 48 and 52C (so 48C was lethal)
- Low temps: Survival of adults exposed to -6C for 240 min resulted in ~10% survival, all individuals died at -14C
- Low temps: Larvae seemed to have more cold tolerance, but most dead by -14C

Source 12. Amanda West's climatic suitability models for USDA-APHIS-CAPS (2017; unpublished report)

- Modeled the global climatic suitability for FCM using five species distribution models (SDMs): generalized linear model (GLM), boosted regression tree (BRT), multivariate adaptive regression splines (MARS), Random Forests (RF), and MaxEnt.
- Models were fit with 57 occurrrence records from the native range and evaluated primarily based on field- and lab- based biological studies of FCM
- Response curves for Bio 5 (max temp warmest month) and Bio 6 (min temp coldest month) covariates indicated that the relative that the relative probability of FCM occurrence increases in environments where the maximum temperature of the warmest month is between 20 and 40° C, and the minimum temperature of the coldest month is between -1 and 20° C



Ensemble average relative probability of climatic suitability for false codling moth (FCM) derived from five species distribution models (generalized linear model [GLM], boosted regression trees [BRT], multivariate adaptive regression spline [MARS], Random Forests [RF], and Maxent



Comparison of model agreement (generalized linear model [GLM], boosted regression trees [BRT], multivariate adaptive regression spline [MARS], Random Forests [RF], and Maxent) for FCM climatic suitability.

Source 13. U.S. Department Of Agriculture, Animal Plant Health Inspection Service, Plant Protection and Quarantine, Emergency and Domestic Programs. 2010. New Pest Response Guidelines: False Codling Moth Thaumatotibia leucotreta. Riverdale, Maryland. [http://www.aphis.usda.gov/import_export/plants/manuals/online_manuals.shtml]

- FCM has established population in geographic areas with climates equivalent to USDA climatic zones 7b through 10a (Fig. 2, below; Venette et al. 2003).

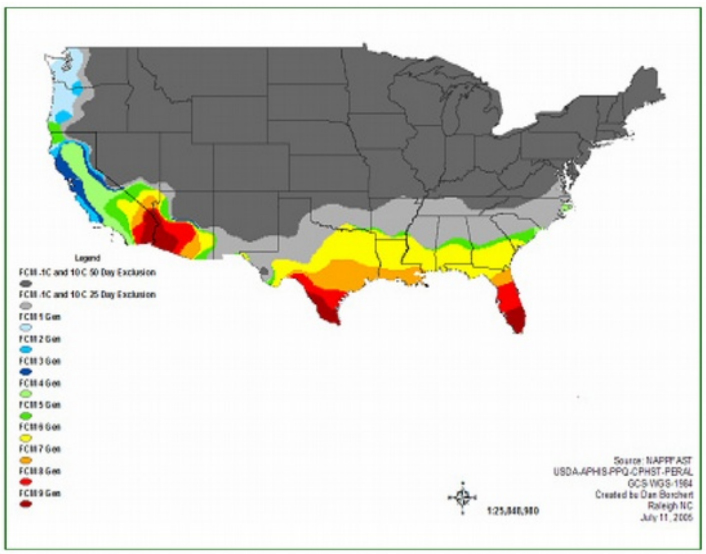


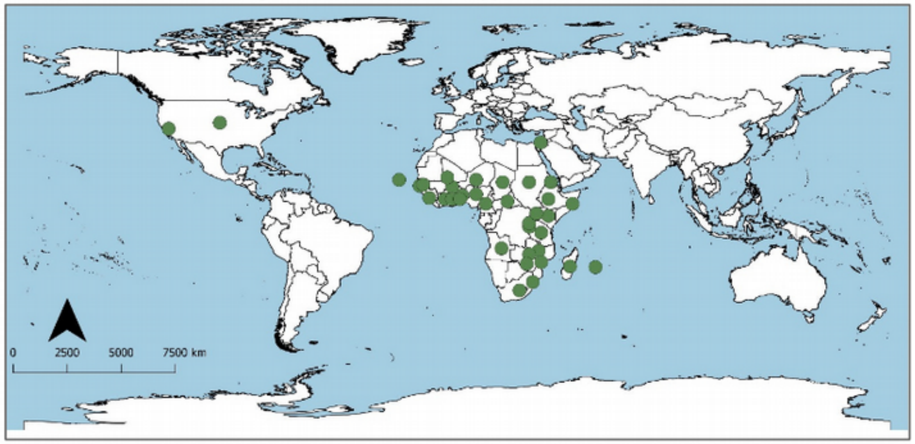
FIGURE 2-2 Estimated potential number of generations of false codling moth. Base developmental temperature is 12°C (53.6°F). Upper developmental temperature is 40°C (104°F). Estimation of generation time is 450 degree days. Two potential exclusion layers exist of 25 and 50 or more days where minimum daily temperature is below -1°C (30.2°F) and average daily temperature is below 10°C (50°F) [Image courtesy of Borchert (2005].

Source 14: S. Africa fact sheet. Online at:
https://www.sun.ac.za/english/faculty/agri/conservation-ecology/ipm/Documents/FCM%20fact%20sheet%20ENG.pdf
last accessed 6/12/19

DISTRIBUTION

FCM is native and widespread throughout sub-Saharan Africa. It also occurs on some Indian and Atlantic Ocean islands such as Mauritius and Madagascar. Since the 1980's FCM has been established in Israel. It was intercepted once in a consignment in the USA in 2008, but extensive surveys did not find established populations of FCM in the USA at that time.

It has occasionally been detected in the Netherlands, UK and Sweden, but these are thought tot be incidental collections and not to originate from established populations as temperatures in these regions are too cold to support permanent populations of FCM.



False codling moth, *Thaumatotibia leucotreta*, distribution. Data from CABI (2017). Map drawn by C.S. Bazelet.

- Established in many countries of sub-saharan Africa; also Israel

Source 15. Citrus Research Institute Fact sheet:
https://www.citrusres.com/system/files/documents/production-guidelines/Ch%203-9-4%20False%20Codling%20Moth%20-%20Nov%202017_0.pdf
last accessed 6/12/19

-Location assumed to be South Africa

“Trap surveys must be initiated in spring and continued until harvest time. The first post-winter peak in moth activity, which reflects a generational peak, usually occurs early in October [March in N. Hemisphere]. This is followed by what is usually a much larger peak in activity, by the subsequent generation, in late Nov or early Dec ([May or June in N. Hemisphere]., depending on the region. …. A peak in moth activity should be followed by a peak in FCM-induced fruit drop 3 to 5 weeks later. This is likely to be particularly evident if trap catches are high.

“On average, there are 6 generations of FCM per year. One might expect all of these generational peaks to be detected by traps. However, this is often not the case. Although, moth activity is fairly well synchronized after winter, as the season progresses, generations begin to overlap with one another to an increaseing extent. Moth peaks may become more blurred and can often be difficult to detect late in the season.

- First post-winter flight peak around March 1 **(**N. Hemisphere**)**

Source 16. Stotter, R.L.. 2009. Spatial and temporal distribution of false codling moth across landscapes in the Citrusdal area (Western Cape Province, South Africa). PhD Thesis. Stellenbosch Univ.

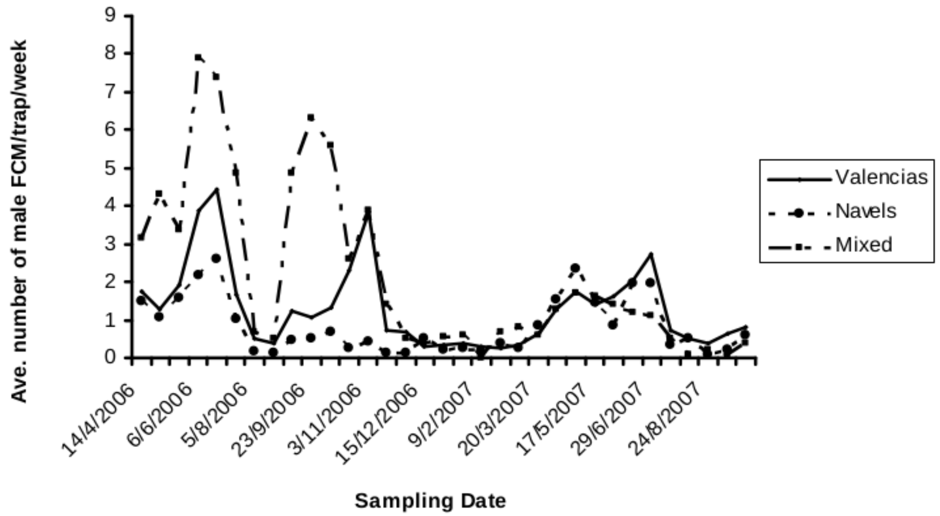


Figure 12. Average weekly trap catches of male FCM in different varieties of citrus in the Citrusdal area (2006-7).

Male FCM activity within citrus orchards peaked between May and June, with a slightly smaller peak in activity between October and November (Figure 13). Trap catches were very low during winter (July – August), probably due to low temperatures as well as a significant increase in the length of the lifecycle of FCM associated with low temperatures (Stofberg, 1954; Daiber, 1978). Trap catches were also low from December to March, when citrus fruit on trees were immature.

- From above, flight in this climate is low in winter (July-Aug; equiv to Jan-Feb).
- Using CLIMEX "match climates", S. Africa citrus regions climate match to Central Mexico (Morellia & Tlaxcala del Xico), also to Brisbane, Australia

- First post-winter flight peak early March **(**N. Hemisphere equiv**)**

Source 17. Malan, A.P., J.I. von Diest, S.D. Moore, & P. Addison. 2018. Control options for false codling moth, Thaumatotibia leucotreta (Lepidoptera: Tortricidae), in South Africa, with emphasis on the potential use of entomopathogenic namatodes and fungi. African Entomol. 26:14-29.

BIOLOGY AND ECOLOGY OF FALSE CODLING MOTH

The majority of the overwintering population consists of pupae, although a small proportion of eggs develop into larvae at low temperatures, with a relatively long developmental duration in the winter months, meaning that there are fewer generations than during the spring and summer (Gunn 1921; Daiber 1980). The wild population ratio of males to females is approximately 1:1 (Daiber 1980; Erichsen & Schoeman 1994; Newton 1998).

- Mainly OW as pupae; assume at cooler parts of its range adults die before springtime warming, so OW as pupae.

18. Estimate of DDs required for springtime first peak in flight

Based on sources #15-17 above: Calc cum Dds over several years at locations in US where FCM could occur, compare to S. Africa and estim. OW degree days to 1st peak flight:
Start Jan 1 end Mar. 1, Tlow = 11.7C Tupper=40C

Location	Code	2015	2016	2017	2018	2019	Avg	1980-2010 Normals
College Station, TX	KCFD	110	178	296	149	124	186.8	109.3
Jacksonville, FL	KVQQ	137	167	327	288	337	279.8	166.3
Tucson, AZ	KDMA	232	230	173	259	153	203.8	155.5
Gainesville, FL	KGNV	175	191	379	319	367	314.0	179.1
using Degreedays.net – Dds for selected citrus regions in S. Africa, equiv 1/1 to 3/1								
Citrusdal, S. Africa	FACT		155	119.4	134.4		136.3	
Greytown, S. Africa	68487		175	239	181		198.3	
Pretoria, S. Africa	68268		296	278	307		293.7	
East London, S. Africa	FAEL		295	258	241		264.7	
Overall Average							234.6	152.55
S.D.							62.1	
average S. Africa only							223.2	
Round to nearest 10 Dds							220	

- Use ca. 220 DDs as first flight peak in spring; nearly fits within pupal development duration (175 DDs), plus preOV (17DD), plus some time for first ripening fruit to serve as hosts (28 DD)

- estimate earlier first flight prior to this time (ca. 160 DDs) for CONUS locations; while flight would likely be earlier in warmer subtropical and tropical regions