Phenology/Degree-Day and Climate Suitability Model Analysis – Vers. 2, June 12, 2020

Analysis by Len Coop and Brittany Barker for USPEST.ORG at Oregon State University, Oregon IPM Center

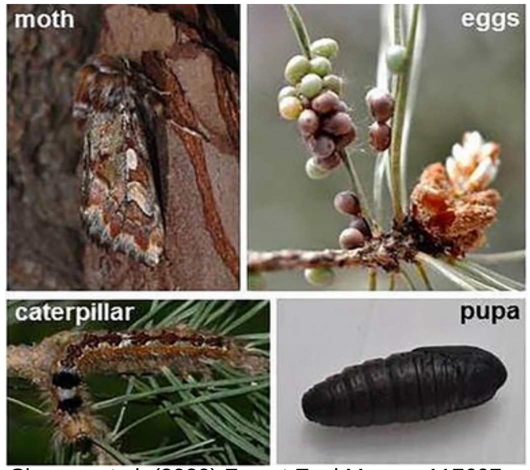
Pine Tree Lappet Moth *Dendrolimus pini* (Linnaeus) [Lepidoptera: Lasiocampidae]

Hosts: *Pinus* spp. esp. *P. sylvestris*; may also attack some spp. of cedar, fir, spruce, juniper

Damage: consumes tree needles

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

Adult *Dendrolimus pini* (L)
Hardin and Suazo (2012)



Skrzecz et al. (2020) Forest Ecol Manag: 117697

Larvae feeding on pine
https://commons.wikimedia.org/wiki/File:Dendrolimus_pini_larva.jpg

Thresholds, degree-days, events and climate suitability params used in Pine Tree Lappet Moth model:

Parameter abbr.	Description	degF	degC	DDF	DDC
eggLDT	egg lower dev threshold	45.0	7.2	-	-
eggUDT	egg upper dev threshold	86.0	30.0	-	-
larvaeLDT	larvae lower dev threshold	45.0	7.2	-	-
larvaeUDT	larvae upper dev threshold	86.0	30.0	-	-
pupaeLDT	pupae lower dev threshold	45.0	7.2	-	-
pupaeUDT	pupae upper dev threshold	86.0	30.0	-	-
adultLDT	adult lower develpmental threshold	45.0	7.2	-	-
adultUDT	adult upper dev threshold	86.0	30.0	-	-
eggDD	duration of egg stage in DDs	-	-	326	181
larvaeDD	duration of larva stage in DDs	-	-	1852	1029
pupaeDD	duration of pupa stage in DDs	-	-	664	369
adultDD	duration of teneral adult stage in DDs	-	-	198	110
OWlarvaeDD	DDs until mid-larval peak	-	-	373	207
eggEventDD	DDs when egg-hatch begins	-	-	324	180
larvaeEventDD	DDs until mid-larval deveopment	-	-	1037	576
pupaeEventDD	DDs until pupae complete development (first adult emerg.)	-	-	657	365
adultEventDD	DDs until first oviposition	-	-	126	70
coldstress_threshold	cold stress threshold	5.0	-15	-	-
coldstress_units_max1	cold stress degree day limit when most individuals die	-	-	684	380
coldstress_units_max2	cold stress degree day limit when all individuals die	-	-	1800	1000
heatstress_threshold	heat stress threshold	86.0	30.0	-	-
heatstress_units_max1	heat stress degree day limit when most individuals die	-	-	342	190
heatstress_units_max2	heat stress degree day limit when all individuals die	-	-	495	275

distro_mean	average DDs to OW larvae first pupation	222
distro_var	variation in DDs to OW larvae first pupation	5000
xdist1	minimum DDs (°C) to OW larvae first pupation	0
xdist2	maximum DDs (°C) to OW larvae first pupation	441
distro_shape	shape of the distribution	normal

(Note points introduced to regression analysis to force x-intercept highlighted yellow)

Sources and Data: **(Note significant data used in final model highlighted in Salmon color)**

1. NAPPFAST Model Documentation Sept 2012

Tlow 3C Tupper 30C (optim. Temp 20C) ← this Tlow is dubious based on studies available below

See "Climate suitability model" section below for risk model (Source 14)

2. Hardin, J.A. and A. Suazo. 2012. New pest response guidelines: Dendrolimus pine moths. USDA-APHIS-PPQ-CPHST.

Available at https://www.aphis.usda.gov/import_export/plants/manuals/emergency/downloads/dendrolimus.pdf

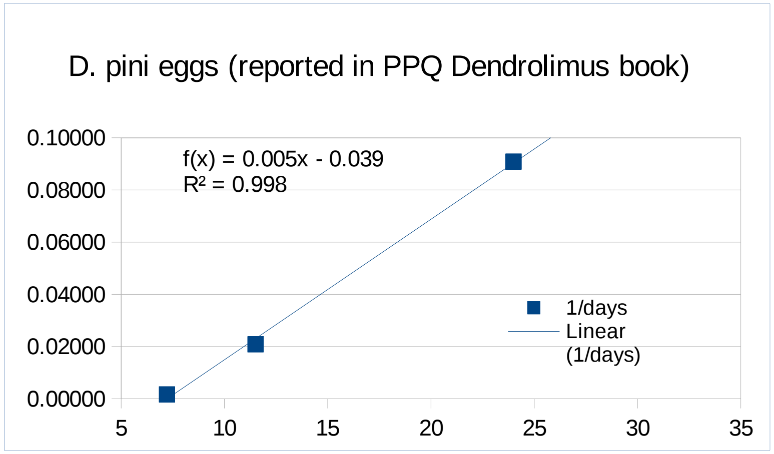
Larvae begin diapause beginning 3rd instar; 4th or 5th instars are OW stage (Heitland 2002)
Larval photoperiodic threshold is 12 hrs daylength or less for 38 days; diapause inhibited at more than 17 hrs. (Geispits etal 1972)
Larvae pupate after 7 or 8 instars
Pupation starts in late spring (May-June and will last 4-5 weeks (Melis 1940)
2 gens/yr in italy otherwise 1-3 years per gen.
Mated females live 7-10 days; unmated 17-20 days; adults do not feed
If 1 gen/yr pupal devel 15 days vs 22 days w/1 gen/2 yr
If 1 gen/yr females dont fly vs do fly w/1 gen/2 yr
Egg devel opt 24C and 80-85% humid, range 14 to 31 C (Kojima 1933)
Temps below 8.5 and above 33.5C result in 100% mortality
Eggs: 10 days at 31.5C to 48 days at 11.5C; 11 days at 24C and 80% RH
Larvae: temp-devel results not mentioned for larvae
Pupae: normal pupation still occurs at 7C; 95 days at 12 C to 14 days at 32C, 25 days at 24C (Kojima 1933, Winokur 1991)
In native range in Europe and Asia, flight normally starts in June and July (Lesniak 1976, Varga 1966)
Flight is conditional: if OW as 4/5th instars, flight mainly in July (univoltine), if OW as 2/3rd instars (winter 1) then as 5/6th instars (winter 2), flight May-June (2 yrs/gen)
Pg 94: flight normally between June and August
See "Climate Suitability Model" below for the risk map that they present

Estimated Adult Female Pre-OV + ca. 40% OV from above (very rough estimate): 8 days at 70 F or 21 C = 8 * (21-7.22) =
110 DD (Tlow=7.22C)

X-intercept regression analyses for eggs based on above reports and 7.22 Tlow

Eggs

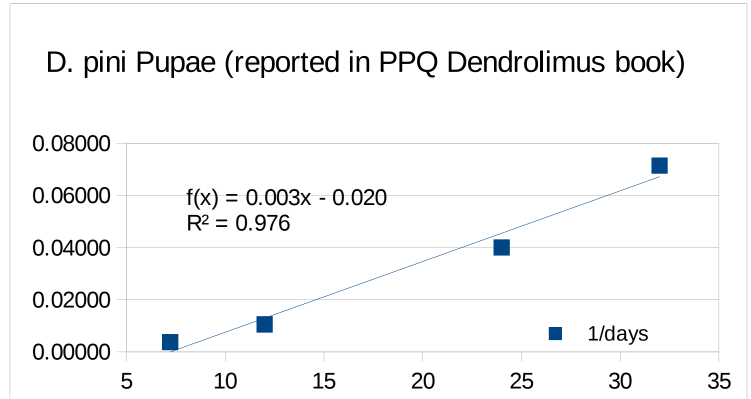
Temp C	1/days	days
7.22	0.00167	600
11.5	0.02083	48
24	0.09091	11
31.5		10
Slope (b)	0.00538	
intercept (a)	-0.03885	
R2	0.99819	
1/slope	185.8	(DD req.)
-a/B	7.22	(x-intercept)



result: incomplete data set; deleted point at supra-optimal temp. (31.5C) allowed easy forcing through x-intecept of 7.22
this resulting value of 186 DD is essentially same as source #3 below

X-intercept regression analyses for pupae based on above reports and 7.22 Tlow

Pupae			
Temp C	1/days	days	
7.22	0.00375	267	
12	0.01053	95	
24	0.04000	25	
32	0.07143	14	
Slope (b)	0.00271		
intercept (a)	-0.01959		
R2	0.97631		
1/slope	**369**	**(DD req.)**	
-a/B	**7.22**	**(x-intercept)**	



result: incomplete data set; fairly good fit; 369 DD best fits with emergence reported Sweden 2012

3. Kojima 1934 and Schwerdtfeger 1963, 1977 – graph of egg development

Original references: Kojima, T., 1934. Studien zur Ökologie des Kiefernspinners, Dendrolimus pini L. Z. angew. Ent. 20:329–353.

Schwerdtfeger 1963 Ökologie der Tire - Parey, Hamburg, 572 pp

Eggs	Focus on Prokhonov 1908: [Fig 2.18 (1)]	
Temp C	1/days	days
10	0.00010	10000.000
14	0.02700	37.037
18	0.05700	17.544
22	0.08300	12.048
26	0.11500	8.696
30	0.14000	7.143
slope (b)	0.00707	
intercept (a)	-0.07101	
R2=	0.9993	
1/slope =	141	
X-intercept= -b/A	10.0	

Focus on Schwerdtfeger 1963: [Fig 2.18 (3)]			
Temp C	1/days	days	
7.28	0.001	2000	
10	0.014	71	
14	0.039	26	
18	0.060	17	
22	0.081	12	
26	0.104	10	
slope (b)	0.0055		
intercept (a)	-0.0399		
R2=	0.9993		
1/slope =	**181**	**(DD req.)**	
X-intercept= **-b/A**	**7.22**	**(x-intercept)**	

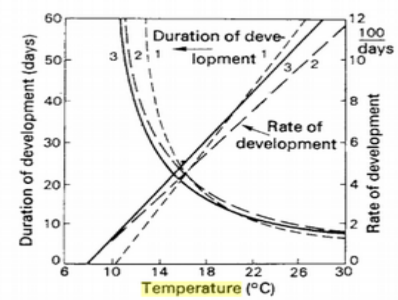
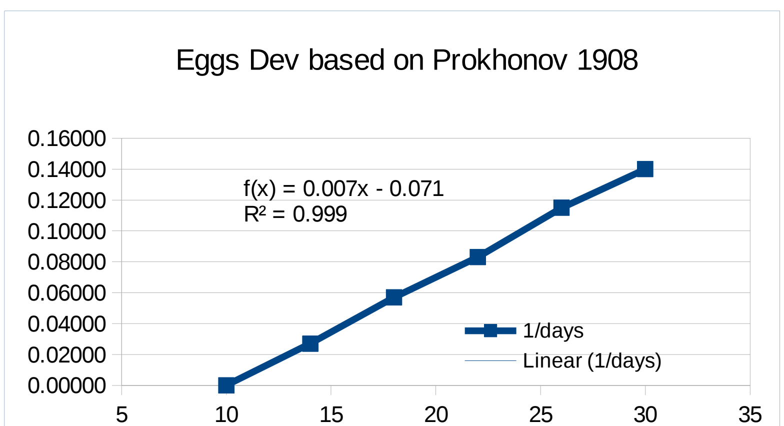
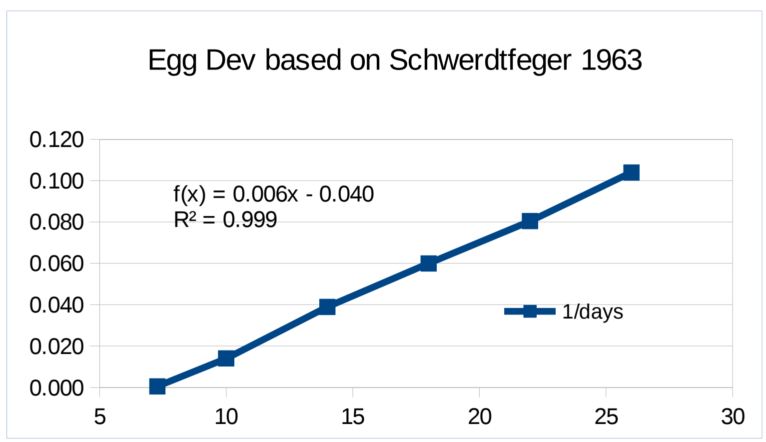


Fig. 2.18 Length and rate of development of eggs of *Dendrolimus pini* (L.) in dependence on temperature (after Schwerdtfeger, 1977): 1 — according to Prokhonov, 1908, 2 — according to Kojima, 1934, 3 — according to Schwerdtfeger, 1963

Based on these works, could use for eggs: Tlow=10 C, 141 Dds, or 7.22 C, 181 Dds (use the latter)





4. CPHST Pest Datasheet Sept 2012

Egg Incub 14-25 days, mortal at or above 32C
OW when daylength 12 hours – larvae move to forest floor to OW in forest litter within 1 m of host tree.
Diapause induced by temps below 5C
Diapause terminated when litter temps reach 3C.
In lab 9hr or less daylight induce diapause for 20-35 days in all instars
Diapause (both sensitivity and response) induced for all larval instars 1962 Ann Rev Entomol

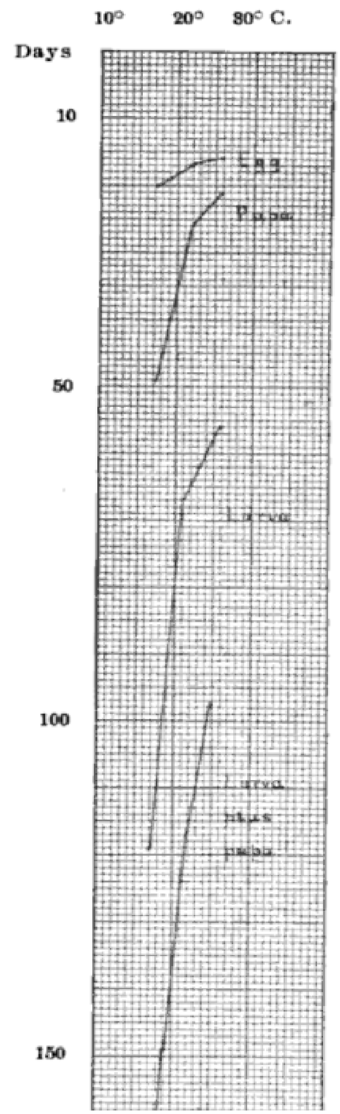
5. Regener and Ratzeburg (from N Hampshire Agric Exp Sta. Sci Contrib. 1910. Pg. 121)

Fig. 13. Temperature development graph of eggs, larvae, pupae, and larvae plus pupae:

normal conditions, record of which we have, have been maintained. In exact work to determine the effect of temperature the moisture conditions should be constant, as with many species the moisture influence is as much or more important than that of temperature in determining the optimum for development.

Similar observations on the time of hatching of the eggs of *Malacosoma americana*, the time of emergence of the caterpillars of the brown-tail moth from their winter nests, the hatching of eggs of the gypsy moth, and the pupal stage of *Samia cecropia*, *Papilio asterias* and *Epargyreus tityrus*, have been or are now being made, but cannot be summarized at present.

Other data is at hand, however, showing the same facts. Thus Kerschbaumer (15) has given data from which the curve for the life cycle of *Culex pipiens* as influenced by temperature has been plotted (figure 12), and Regener (21) and Ratzeburg (20) have shown the same for the different stages of *Dendrolimus pini*, shown in figure 13. One of the most careful studies of the relation of both temperature and moisture to the development of an insect is a recent one of Hennings (9) with *Tomicus typographus* Linn. Hennings reared all stages and secured the complete life cycle of this species at four

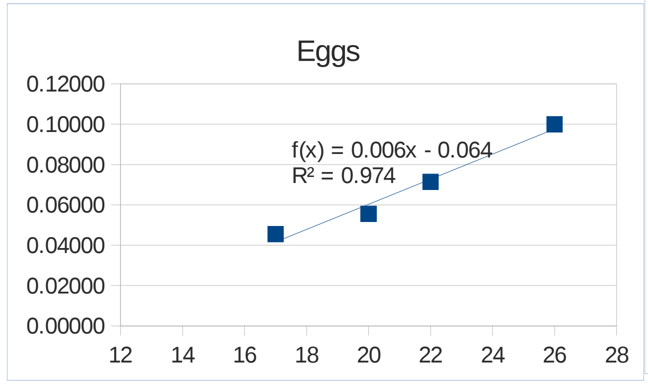


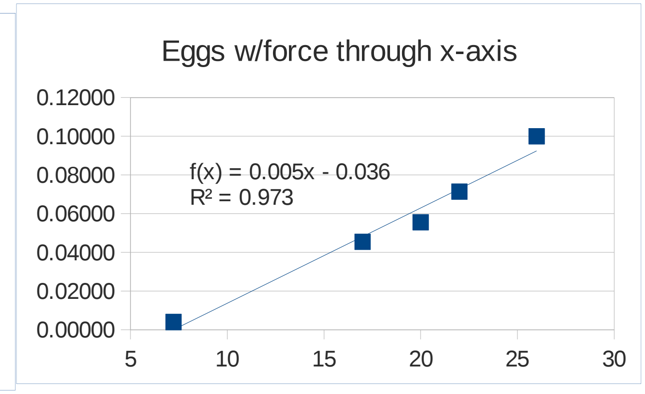
From above figure (with forcing through proposed Tlow of 7.22 C):

X-intercept regression analyses:

Egg	Temp C	1/days	Days
	7.22	0.00395	253
	17	0.04545	22
	20	0.05556	18
	22	0.07143	14
	26	0.10000	10
	slope	0.00492	
	intercept	-0.03555	
	R2	0.97280	
	1/slope	203	
	-a/B	7.22	

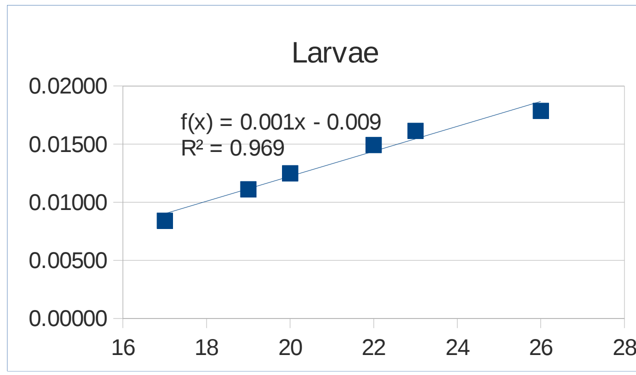
Notes: similar to earlier examined studies; use those results

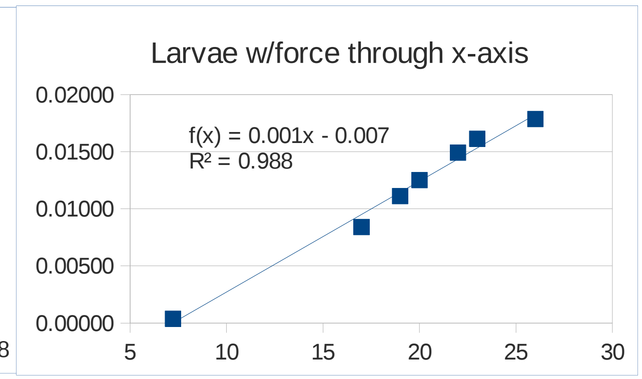




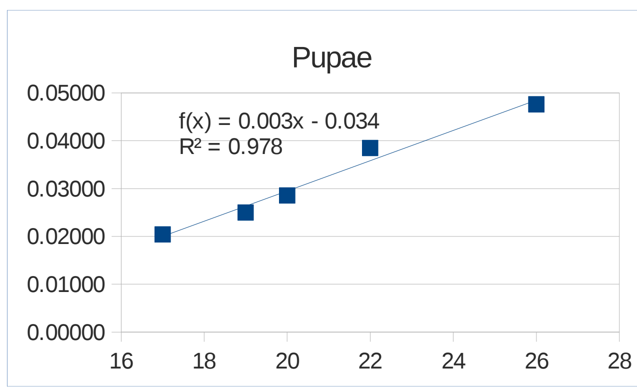
Larvae	Temp C	1/days	Days
	7.22	0.00038	2650
	17	0.00840	119
	19	0.01111	90
	20	0.01250	80
	22	0.01493	67
	23	0.01613	62
	26	0.01786	56
	slope	0.00097	
	intercept	-0.00701	
	R2	0.98762	
	1/slope	**1029**	**(DD req.)**
	-a/B	**7.22**	**(x-intercept)**

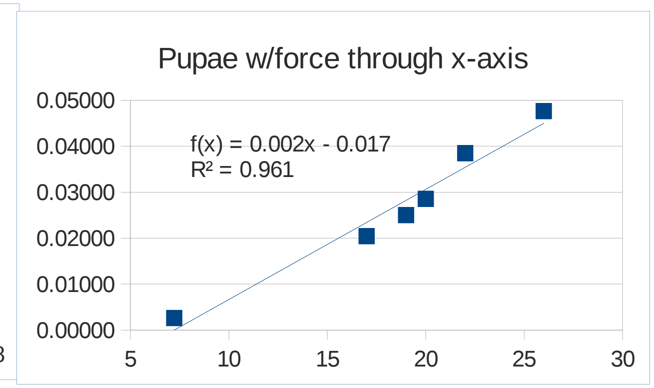
Notes: best avail. Data for larvae; Tlower of 7.22 seems to be a good fit.





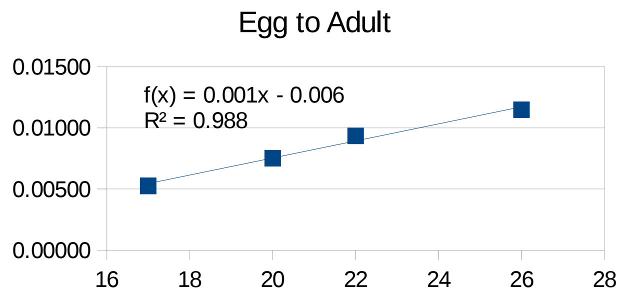
Pupae	Temp C	1/days	Days
	7.22	0.00267	375
	17	0.02041	49
	19	0.02500	40
	20	0.02857	35
	22	0.03846	26
	26	0.04762	21
	slope	0.00240	
	intercept	-0.01730	
	R2	0.96076	
	1/slope	417	
	-a/B	7.22	

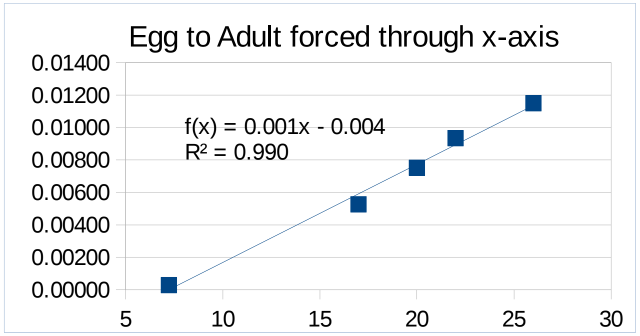




Egg through Pupae

	Temp C	1/days	Days
	7.22	0.00029	3500
	17	0.00526	190
	20	0.00752	133
	22	0.00935	107
	26	0.01149	87
	slope	0.00060	
	intercept	-0.00436	
	R2	0.99005	
	1/slope	1655	
	-a/B	7.22	





5.1. Summary from all highlighted data above:

				Sum	Regression	
	Egg	**Larvae**	**Pupae**	**Egg to Adult**	Egg to Adult	**Pre-OV+40% OV**
DDs	**181**	**1029**	**369**	**1579**	1655	**110**
Tlow	**7.22**	**7.22**	**7.22**	**7.22**	7.22	**7.22**

From these results: estimate Tlow: 7.22 C, egg to adult devel: 1579 DD, generation time: 1689 DD

6. Meshkova, V. 2004. Dependency of outbreaks distribution from insects-defoliators' seasonal development (Ukraine). Proceedings: Ecology, Survey and Management of Forest Insects GTR-NE-311: 52-60.

"the interval between dates of air temperature transition over 5 and 10C with D. pini….it is during this period that larvae initiate feeding after hibernation. ...transition below 5 and 0 in autumn is also reliable. This is during the period when winter diapause of D. pini caterpillers begins.

Interpretation: including photoperiod (threshold 12:12 L:D) would be a good way to terminate and then initiate diapause in spring and fall; but finding an appropriate Tlow that tends to correspond with non-diapause activity could work well also. Thus 7.22C may fit these analyses of spring and fall activity.
Two D. pini gens per year occur in the South, only one gen. In the North of Ukraine
In outbreak years, first gen. Cocoons were formed before June 17 in 88.2% of cases; majority of first gen. Larvae complete feeding before the solstice (June 21)
Late devel. Larvae may go through a summer diapause and then will coincide with larvae from the summer generation.

7. Pest Alert (UK Forestry Commission) – Pine Tree Lappet Moth (2009) – possibly established near Inverness, Scotland

Adult moths emerge between late June and mid August and live for 9-10 days.
Eggs hatch after 16-25 days during August and Sept.
Larvae begin feeding on edges of pine needles. Autumn feeding lasts for 2-3 moults until the first frost, when larvae migrate down the tree to OW beneath the litter at the litter/mineral soil interface, usually very close to the tree trunk.
This devel. Stage ends in early spring, when soil temps reach 4-5C. The larvae then return to the pine canopy and feed on old needles.
Pupae devel occurs in May-June and lasts 4-5 weeks.

8. Grodner, J. and R. Zander. 2010. Sex pheromone of the pine tree lappet moth *D. pini* and its use in attarctant based monitoring system. Pestycydy/Pesticides 1-4:43-49

D. pini males were trapped 5 July to 13 August 2010. In the Slawa Slaska Forest District (Zielona Gora) Poland

		Date	DDs	
Nearest German data found:		Date	DDs	
	3376	07/06/10	580	approx first flight (according to data)
Muncheberg (E of Berlin)		08/14/10	1091	approx end of flight (accord. To data)

(modify Jun and July with data from Leszno, Poland; Climate diffs between Berlin and Poznan Poland are small)
wea file:
SLAWA210.txt **NOTES: Corresponds pretty well with the model at least for beginning of flight**

9. Priesner, E., H. Bogenschutz, D.W. Reed et al. 1984. Identification and field evaluation of a sex pheromone of the European Pine Moth. Z Naturforsch C J Biosci. 39:1192-1195

D.pini flight season usually begins in central Europe in early July – beginning of 1983 flight season was apparently missed, but the mid-July peak was covered.

Seewiesen (SW of Munich)	06/25/82	06/29/82	07/06/82	07/13/82	07/20/82	07/27/82	08/03/82	08/17/82
Germany: approx % flight:		3.8	19.1	37.4	22.9	12.2	1.5	0
sta. Numbers 3379,3385								

		Date	DDs	
Best Match→	1982 SEEWIES1 Germany	Date	DDs	
	Station code 3379	06/25/82	574	approx first flight (model and data)
	wea file:	07/18/82	866	approx first egghatch (model)
	SEEWIES182.txt	07/26/82	987	approx peak flight (model)
		07/17/82	862	approx peak flight (accord. To data)
		08/29/82	1371	approx end of flight (model)
		08/14/82	1211	approx end of flight (accord. To data)

seems a poor match→	1982 SEEWIES2 Germany	Date	DDs	
(leave out of	Station code 3385	07/04/82	574	approx first flight (model)
average below)	in Munich	07/28/82	866	approx first egghatch (model)
	at Nymphenburg	08/08/82	987	approx peak flight (model)
	wea file:	07/17/82	746	approx peak flight (accord. To data)
	SEEWIES282.txt	08/14/82	1066	approx end of flight (accord. To data)

Breisach (W. of Freiburg, S.	07/04/83	07/12/83	07/19/83	07/26/83	08/02/83	08/09/83	08/16/83
(w of Freiburg, s of Strasbourg) Germany		19.6	39.2	28.3	9.3	1	2.6
station codes 1443,1447,1451							

1983 BREISACH1 Germany	Date	DDs	
Station code 1443	06/13/83	574	approx first flight (model)
wea file:	07/08/83	866	approx first egghatch (model)
	07/16/83	987	approx peak flight (model)
BREISACH183.txt	07/18/83	1032	approx peak flight (accord. To data)
	08/10/83	1379	approx end of flight (model)
	08/18/83	1483	approx end of flight (accord. To data)

1983 BREISACH2 Germany	Date	DDs	
Station code 1447	06/16/83	574	approx first flight (model)
wea file:	07/11/83	866	approx first egghatch (model)
	07/18/83	987	approx peak flight (model)
BREISACH283.txt	07/16/83	1026	approx peak flight (accord. To data)
	08/15/83	1379	approx end of flight (model)
	08/18/83	1423	approx end of flight (accord. To data)

Average DDs for Events based on flight data from 8 & 9 above:

574	**approx first flight (accord. To data)**
973	**approx peak flight (accord. To data)**
1372	**approx end of flight (accord. To data)**

Interpretation: The first flight for 1982 matches well with reported data (ca 574 DD; ca. Week of June 22-29)

The first flight for 1983 was not monitored but could have been in range of model prediction; ca. Week of June 10-17)

Peak flight for 1982 matched well (ca 862 DD data vs 987 DD model, ca. 7/17/82 data vs 7/26/82 model)

Peak flight for 1983 matched well (ca 7/16-18/83 for both weather station locations.)

End of flight was underpredicted by two weeks for 1982 data, nearly the same date for 1983 data.

These results appear to reflect overwintering not as ready-to-pupate prepupae (as with #10 and #11 below), but as mid-to late instar larvae that will further feed and pass through one or more molts before pupating in the spring. Thus, these results will be used to represent all but the most northern/coldest regions of this insects distribution.

10. Ostrauskas, H. and P. Ivinskis. 2011. Moths caught in pheromone traps during search for *Dendrolimus pini* and *D. sibiricus* (Lepidoptera: Lasiocampidae) in Lithuania. Acta Zool. Lithuanica 21:238-243.

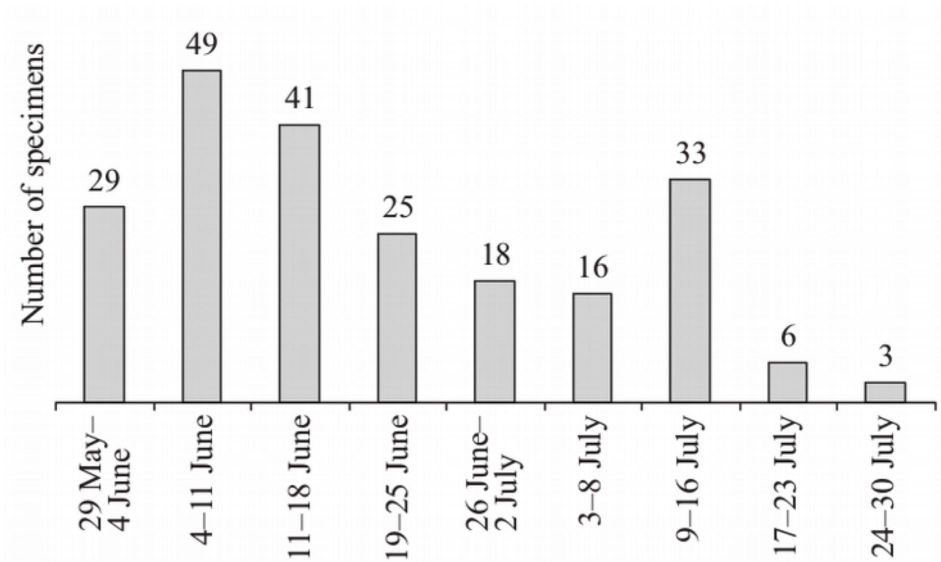


Figure 1. Number of *Dendrolimus pini* moths caught by light trap of Jalas model in Šarkiškė (Švenčionys district) during 1995 (no-one specimen of this species was trapped by light trap before and after indicated dates).

1995 Berlin — **data in Fig. 1 – moths caught by light traps in Sarkiske 1995**
Climate average
1-2 deg C warmer avg. Tmax and ca same Tmin for months of Mar-July
vs. Vilnius Lithuania (data adjusted for climate differences)

SARKISK95.txt	Date	DDs	DDs (not adjusted for climate diffs Berlin vs. Lithuania)	
SARKNA95.txt (not adj.)	06/15/95	334	359	approx first flight (accord. To data)
	07/12/95	621	649	approx peak flight (accord. To data)
	07/30/95	861	893	approx end of flight (accord. To data)

NOTES: this report indicates flight can occur earlier than model predicts by ca. 200-300 Dds;
This pattern essentially shows that larvae have completed feeding and development by winter and only need to complete the pupal stage in the spring

Revise above analysis 4/29/20 using degreedays.net data from nearest weather stations and using recent year data (2017-2019):

weather station names and codes:		#1: Lyntupy VI 26645			**#2: Vilnius, LI EYVI**				
		Lyntupy			Vilnius				
		2017	2018	2019	2017	2018	2019	Average	S.D.
Event	**Date**	DDs							
ca. 1st flight	06/15/95	295	502	490	340	586	541	459	116
ca. peak flight	07/12/95	521	753	756	589	856	829	717	134
ca. end flight	07/30/95	688	1001	941	774	1113	1029	924	162
	12/31/95	1204	1632	1503	1336	1813	1657	1524	224

Results: As expected from planet warming, the recent data Dds are higher than, but within range as compared to data from the year 1995.

Again, this represents a population for Northern/colder regions that overwinter as prepupae ready to pupate as soon as temperatures warm in the spring

11. Björkman, C., A. Lindelöw, K. Eklund et al. 2013. A rare event - an isolated outbreak of the pine tree lappet moth in Stockholm archipelago (Sweden). Ent. Tidskr. 134:1-6.

Female lays 15-350 eggs on branches and stems in July. Eggs hatch after 2-3 weeks. Larvae develop through 6 instars and may be completed after 1 or 2 Hibernations. In Oct half-grown larvae hibernate in soil. Post 2nd-hibern. Larvae will pupate in May or early June. In southern Sweden the larvae develop into adults already in the second summer and emerge in July.

2012 STCKHLM Sweden	Date	DDs	event
	07/05/12	400	approx first flight (accord. To data)
	09/12/12	1073	approx end of flight (accord. To data)
	09/18/12	1108	numerous small larvae present (accord. To data)
	07/02/12	370	approx first flight (model – colder regions)
	09/01/12	992	Approx. end of flight (model - colder regions)
	10/09/12	1174	larvae seek OW hibernacula (model)
2012 SVENSKA Sweden	07/05/12	262	approx first flight (accord. To data)
	09/12/12	924	approx end of flight (accord. To data)
	09/18/12	954	numerous small larvae present (accord. To data)
	07/16/12	364	approx first flight (model – colder regions)
	09/27/12	992	Approx. end of flight (model - colder regions)
	NA	1174	larvae seek OW hibernacula (model)

NOTES: like in Lithuania, Sweden is a Northern/cold site that may have 3 yrs/generation and OW as prepupae

Average DDs for Events based on 10 & 11 above: **Note: these cases seem to support a 2-3 yr/generation model whereby mature larvae/prepupae OW**

367	approx first flight (accord. To data)
667	approx peak flight (simple avg of first and end of flight)
967	approx end of flight (accord. To data)

Summary of Phenology Model for *Dendrolimus pini* (Pine Tree Lappet Moth):

Start Date:	**January 1st**			
Calc Method:	**Single Sine**	**Deg. C**	**Deg. F**	
Tlower:		7.22	45	
Tupper:		30	86	
Primary Events		**DD C**	**DD F**	
OW late instar Larvae-Adult Emerge		574	1034	(est. based on 20% larval+pupal dev.)
Egg		181	326	
Larvae		1029	1852	
Pupae		369	664	
Egg to Adult		1579	2842	
Pre-OV+40% OV		110	198	(from #2 above)
Generation Time		1689	3040	
Events Table				
In northern/colder regions: first adult flight from late instar OW larvae		367	661	
1st Gen. Adult Emerg. (most regions)		574	1034	
1st Eggs Hatch from spring adult egglaying (most regions)		866	1558	
Approx. peak adult flight (most regions; end of flight colder regions)		973	1752	
Early-mid larval instars seek hibernacula (if after Oct 1)		1174	2114	
Approx. end of adult flight (except colder regions)		1372	2470	
Mid-late larval instars seek hibernacula (if after Oct 1)		1483	2669	
2nd Gen. Adult Emerg (only in warmest regions)		2263	4074	
1st Eggs Hatch from 2nd Gen. adult egglaying (if any)		2555	4598	

Climate Suitability Model

12. Ray, D., Peace, A., Moore, R. et al. 2016. Improved prediction of the climate-driven outbreaks of *Dendrolimus pini* in *Pinus sylvestris* forests. Forestry. 89:230-244.

- Used published data of damaging outbreaks plus historical climate data from Germany to build a relationship between climate and outbreaks, and develop a prediction model
- Methods used a PC analysis and decision-tree data mining

In Scotland, more detailed analysis w/ probabalistic climate change projections showed an increasing risk of outbreaks through the 21st century

13. Molet. 2012. CPHS pest datasheet for *Dendrolimus pini.* USDA-APHIS-PPQ-CPHST.

- The known distribution suggsts that the insect may occur in 2 biomes in the U.S.: (1) temperate confierous forests; and 2) temperate broadleaf and mixed forests
- Both biomes account for approx. 47% of the area of the U.S. (see map below)

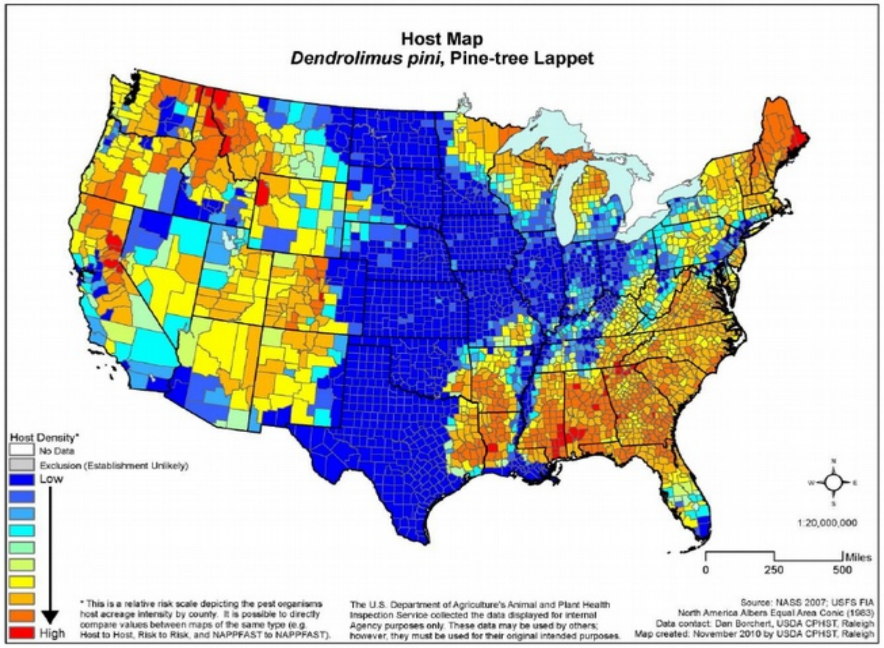
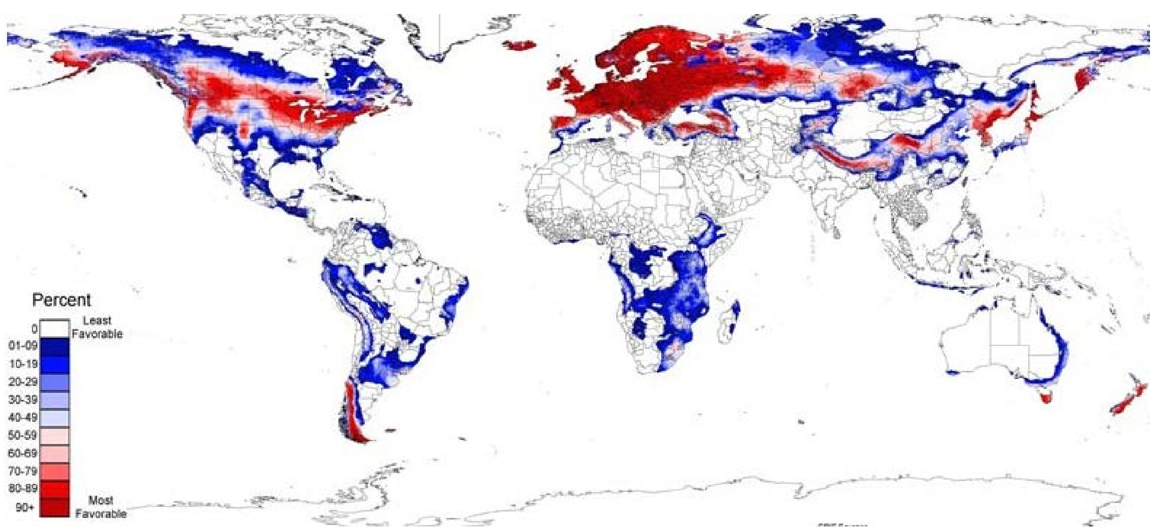


Figure 3. Host map for *D. pini* within the continental United States. Values from low to high indicate increased risk based on host availability. Map courtesy of USDA-APHIS-PPQ-CPHST. Check www.nappfast.org for the most recent map updates.

14. NAPPFAST. Risk models found via a "NAPPFAST Dendrolimus pini" search and in Hardin and Suazo (2012) (Source 1)

- Parameters used for model are unclear - could only find the below image
- They conclude that the risk of establishment is greatest in coniferous forests in hardiness zones 4-7 inc. in the southern Appalachian mountain range, the northeast, midwest (Minnesota, Michigan, Wisconsin, North Dakota), and the northwest regions of the United States and Alaska

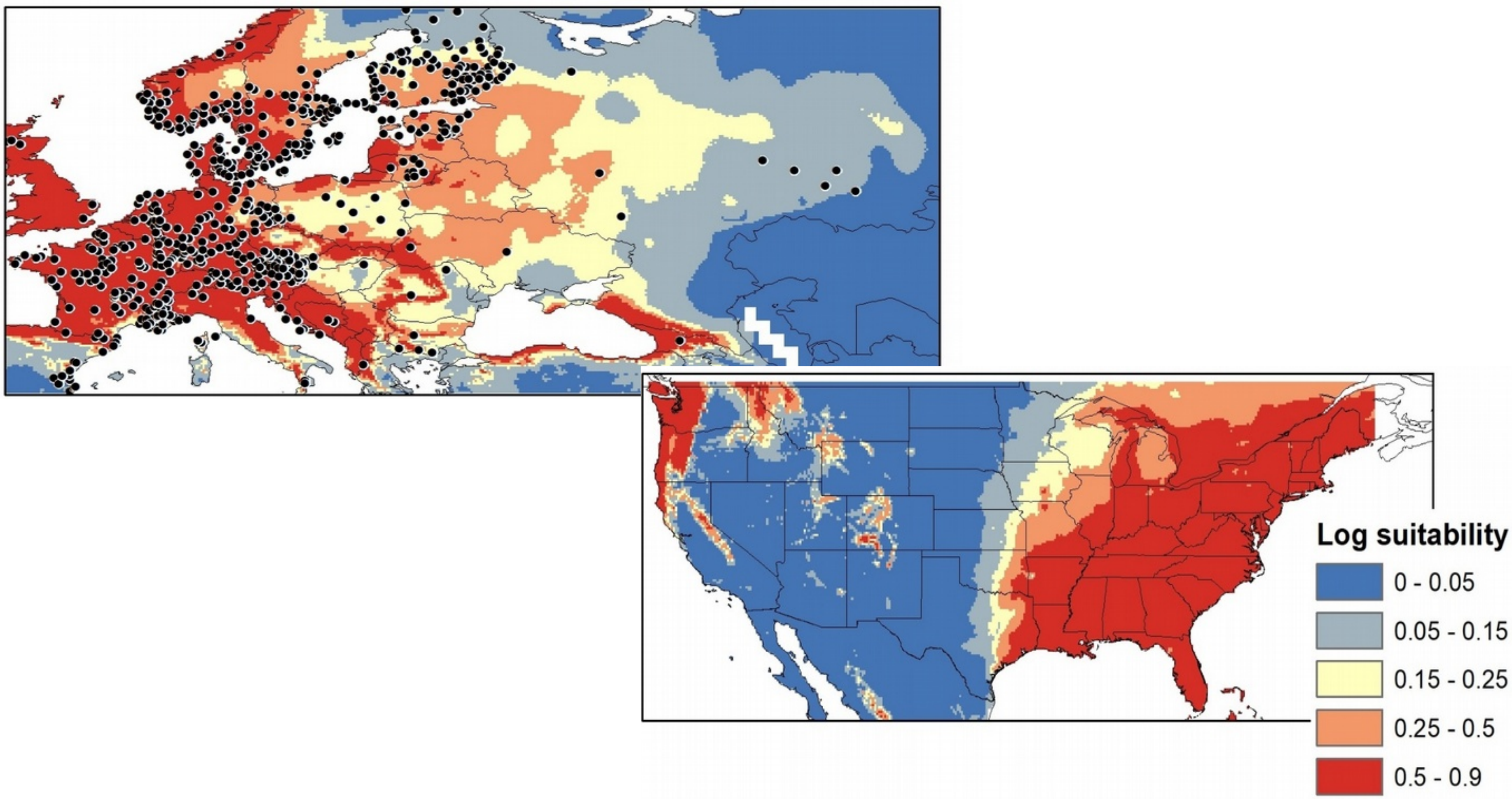


15. Lesniak, A. 1976. Climatic and meteorological conditions of the pine moth (*Dendrolimus pini* L.) outbreaks. Ecologia Polska 24:515-547.

- The study reported climatic and meteorological conditions in 6 of the most important centers of outbreaks in Poland
- Areas with the most dangerous outbreaks have average annual temps of 7.8C; weaker outbreak centers were 6.9 and 7.2C
- Frydrychewicz (1934) indicated 100% mortality of the first larval instar at temps >30C
- Outbreaks occur in areas where isotherms of July oscillate at minimum around 18C (this supports a values of 20C as optimal for the species)
- The optimum for development in respect to isotherms of the coldest month (January) is close to the -2C isotherm
- Below the -3.5C isotherm outbreaks are lower in intensity
- Outbreaks are lower in areas where the number of frost days (max temp <0C) exceeds 50 days
- The most severe outbreaks are in the driest areas of Poland, where the average total precip of the warm half of the year is < 350 mm
- They conclude that high temperatures and low humidity are ideal conditions for the species in Poland

16. Maxent model (this study)

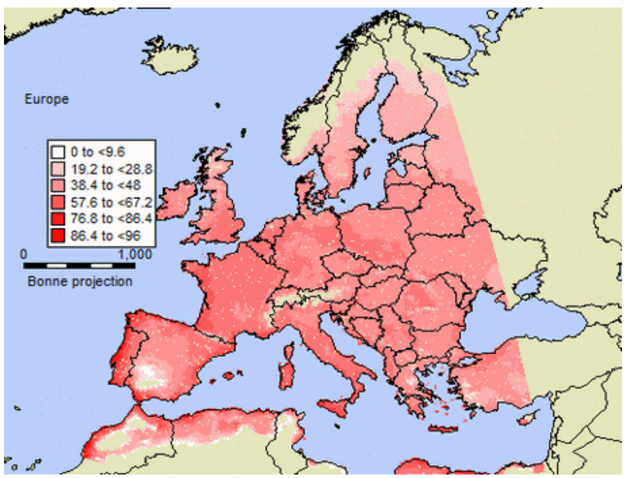
- Used locality records from GBIF and the literature to conduct a correlative niche model analysis (Maxent)
- As described in the white paper, the records were subsampled to reduce geographic sampling bias, resulting in 600 records
- Methods included 50 replicates, with a random 80% of localities used to train the model and 20% reserved for testing using the AUC statistic
- Input climate data were the first 2 principal components of Bioclim variables 1-19 (https://www.climond.org/BioclimData.aspx)
- Other settings were default



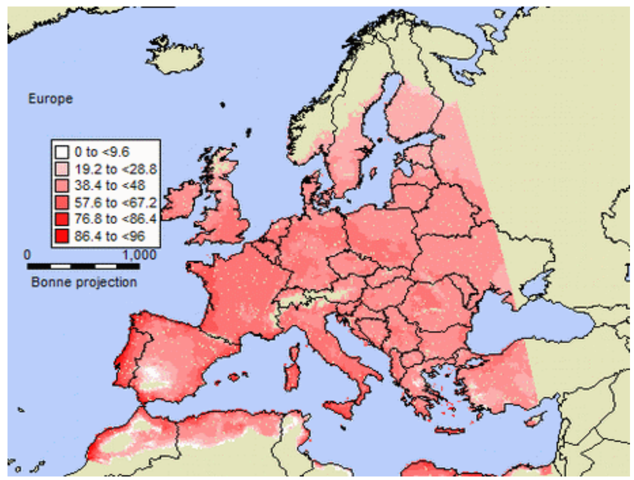
17. CLIMEX model (this study)

- The species is semi-voltine in northern parts of Europe, but CLIMEX analyses are based on a single year, so it considers an area to be unsuitable if a full gen. is not completed in a year
- Moore et al. (2017) reported that moths overwinter twice as larvae in Scotland (2 year life cycle), similar to Bjorkman et al. 2013 (Source 11)
  Moore, R.,Cottrel, J., Hara, S., Ray, D. 2017. Pine-tree lappet moth (Dendrolimus pini) in Scotland: Discovery, timber movement controls and assessment of risk in *Pinus sylvestris* forests. Scottish Forestry. 71:34-43.
- Therefore the species likely overwinters a second time as a late larval instar (pre-pupa)
- The generation time parameter (PDD) in CLIMEX was set to 515, which is equal to 50% of the larvaeDD (i.e. 50% of 1029DD)
- So EI only represents the ability for the moth to persist at a location - i.e. OWlarvae can make it to the second OWlarvae stage for the year
- The resulting map of EI in Europe is very consistent with locality records for the species - localities in Scandinavia (see Source 16 map) were not excluded, whereas they were excluded when a higher PDD was used
- The heat stress parameters (TTHS and THHS [rate]) were adjusted so that areas of exclusion in US SW generally matched NAPPFAST model (Maxent also predict low suitability there)
- The cold stress parameter (TTCS) value of -15C was chosen because one of the most northerly locatility records for the species (near Kuusamo, Finland) has an average low-temp of -18C, and using this value resulted in the inclusion of the majority of localities in Scandinavia

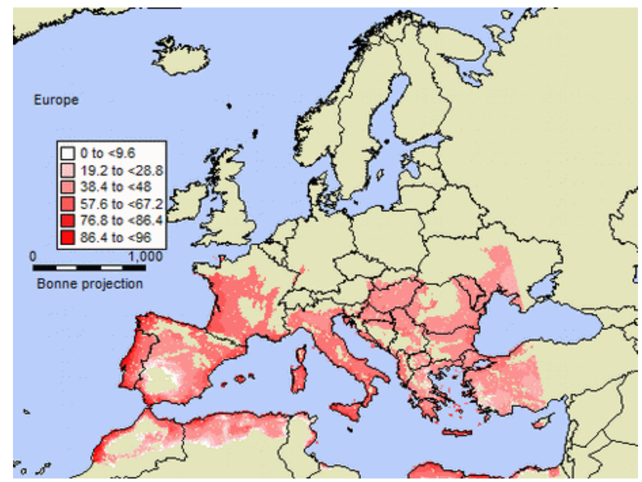
PDD = 515
(50% of larvaeDD)



PDD = 654
(OWlarvaeDD + adultDD + eggDD)



PDD = 1689
(Full generation)



Final CLIMEX parameters

Moisture Index

SM0	SM1	SM2	SM3
0.1	0.3	1.7	2.5

Temperature Index

DV0	DV1	DV2	DV3
7.2	13	23	30

Cold Stress

TTCS	THCS	DTCS	DHCS	TTCSA	THCSA
-15	-0.001	0	0	0	0

Heat Stress

TTHS	THHS	DTHS	DHHS
31	0.01	0	0

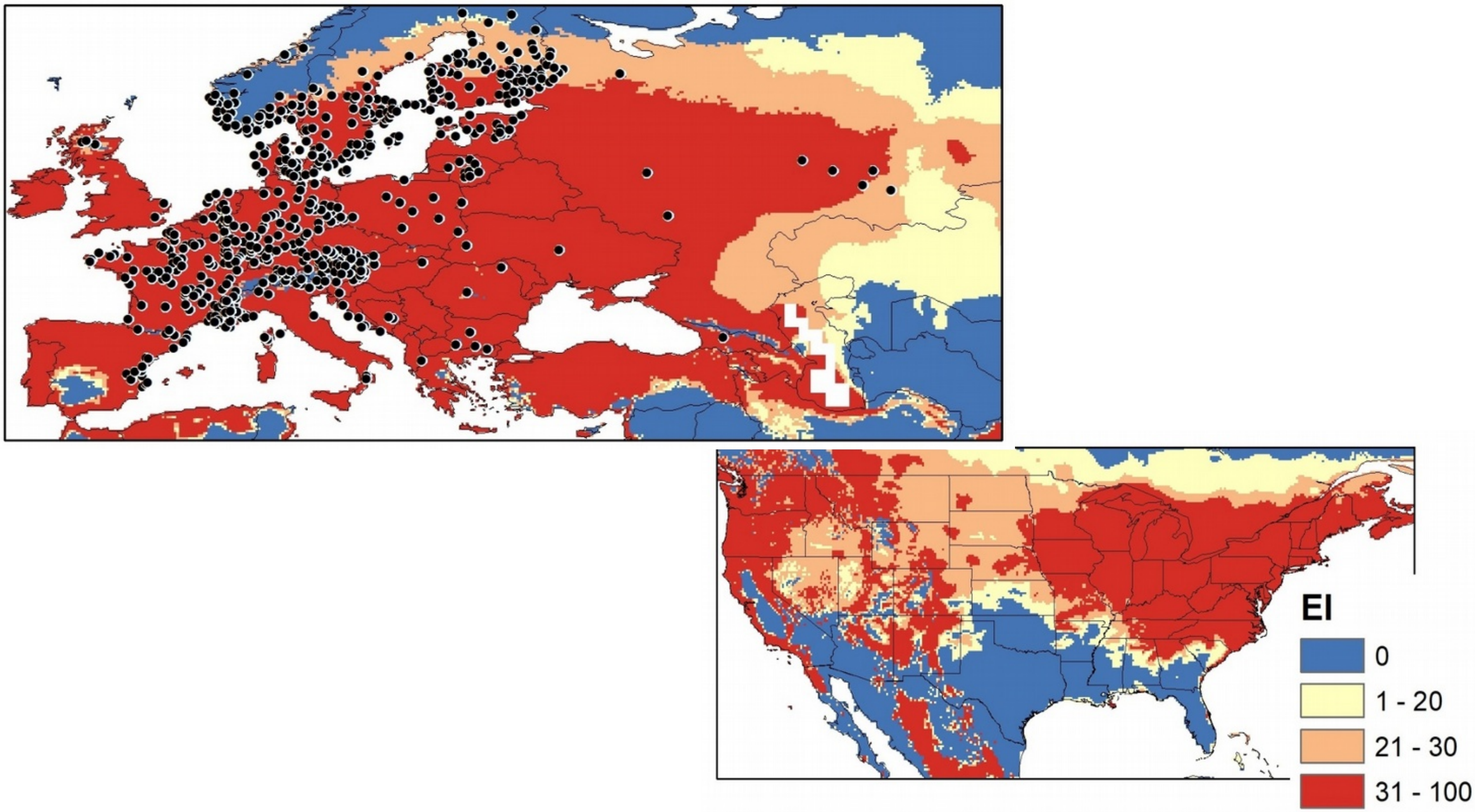
Dry Stress

SMDS	HDS
0.1	-0.01

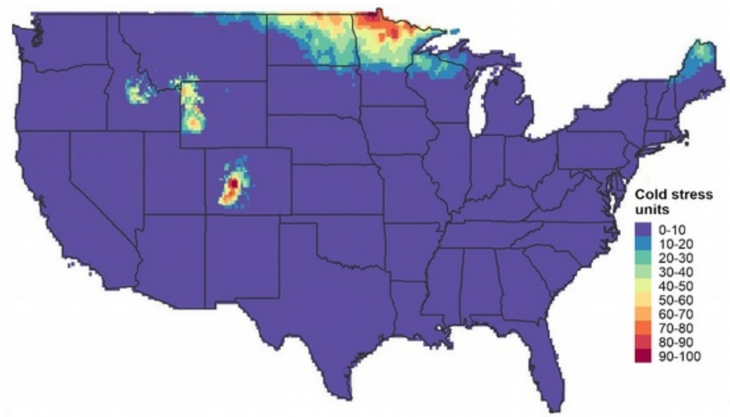
Wet Stress

SMWS	HWS		
	2.5	0.0003	
Day-degree accumulation above DV0			
DV0	DV3	MTS	
	7.2	30	7
Day-degree accumulation above DVCS			
DVCS	*DV4	MTS	
	-10	100	7
Day-degree accumulation above DVHS			
DVHS	*DV4	MTS	
	31	100	7
Degree-days per Generation			
PDD			
	515		

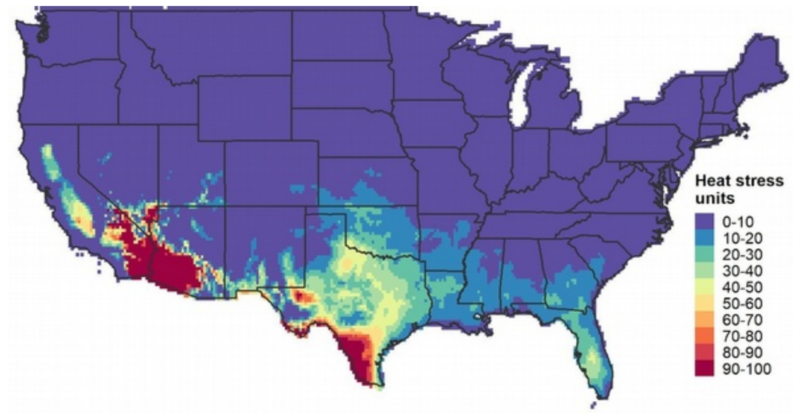
CLIMEX Ecoclimatic Index - Europe vs. North America



CLIMEX Cold Stress (CONUS)



CLIMEX Heat Stress (CONUS)

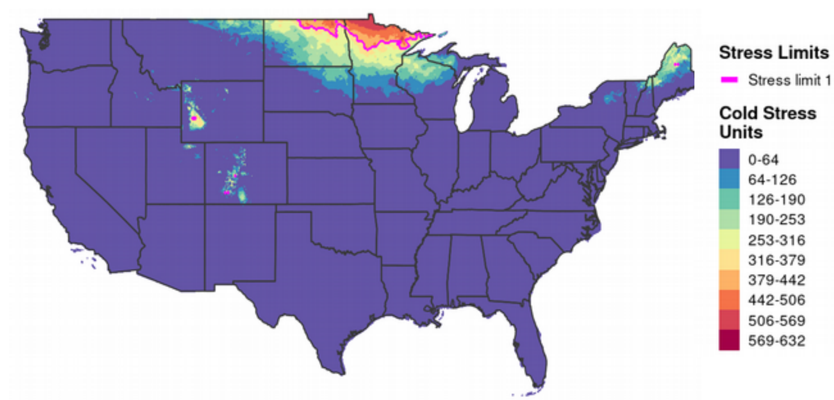


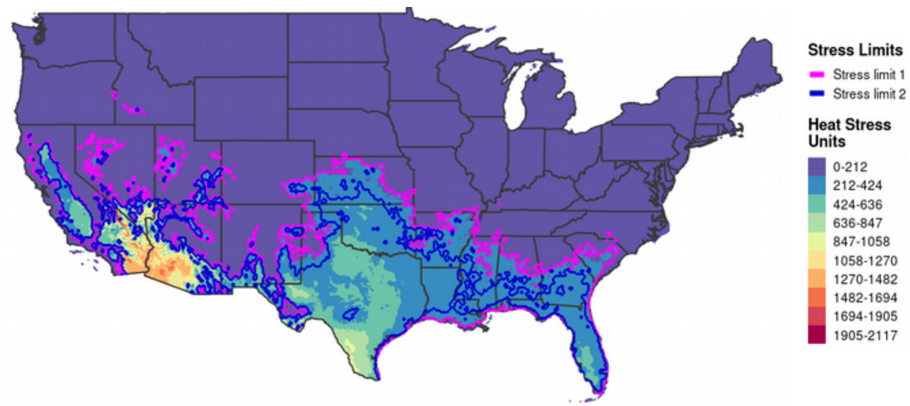
18. DDRP climate suitability model

- Developed primarily based on CLIMEX model results- using daily downscaled 1961-1990 normals to allow CLIMEX calibration
- limit2 for severe cold stress may need to be fine-tuned; setting a value was difficult because according to CLIMEX the climate only becomes unsuitable in Canada

DDRP Cold Stress	Value	Units
cold stress threshold	-15	C
limit 1 (mod. cold stress)	380	DDC
limit 2 (sev. cold stress)	1000	DDC

DDRP Heat Stress	Value	Units
heat stress threshold	30	C
limit 1 (mod. heat stress)	190	DDC
limit 2 (sev. heat stress)	275	DDC





DDRP All Stress exclusion