Supplementary Materials

`dynamAedes`: a unified modelling framework for invasive *Aedes* mosquitoes

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Contents

1 Review of mechanistic model for invasive *Aedes*

Name	**Year**	**Parameterized for (species)**	**Dispersal**	**Programming language**	**Reference**
CIMSiM	1993	*Ae. aegypti*	No	Visual Basic	Focks et al. (1993b,a)
SkeeterBuster	2009	*Ae. aegypti*	No	C++	Magori et al. (2009)
`stagePop`	2009	Generic	No	R	Kettle and Nutter (2015)
	2011	*Ae. albopictus*	No	C++	Poletti et al. (2011)
ALBORUN	2013, 2019	*Ae. albopictus*	No	Ocelet	Tran et al. (2013, 2020)
`sPop`	2018	Generic	No	C++, R, Python	**?**
`albopictus`	2019	*Ae. albopictus*	No	C++, R, Python	Erguler et al. (2016, 2017)
	2019	*Ae. albopictus*	No	Octave v4.2.1, Runge–Kutta 4	Metelmann et al. (2019)
	2019	*Ae. koreicus*	No	R	Marini et al. (2019b)
ARBOCARTO	2019	*Ae. albopictus*, *Ae. aegypti*	No	Ocelet	Tran and Demarchi (2019)
	2020	*Ae. aegypti*	No	R	Iwamura et al. (2020)
	2020	*Ae. koreicus*	No	R	Kurucz et al. (2020)
	2020	*Ae. albopictus*	No		Pasquali et al. (2020)
	2021	*Ae. aegypti*	Yes	R	Da Re et al. (2021)
ALBOMAURICE	2021	*Ae. albopictus*	No	Ocelet	Iyaloo et al. (2021)
	2022	*Ae. japonicus*	Yes	R	Kerkow et al. (2022)
dynamAedes	2022	*Ae. aegypti*, *Ae. albopictus*, *Ae. japonicus*, *Ae. koreicus*	Yes	R	This study

Table 1: Description of mechanistic models for invasive *Aedes* available as software or scripts (online or on request).

2 Parameters used in `dynamAedes`

Species	Stage	Parameters	Main data source	Origin	Value	Comments
Ae. aegypti and Ae. albopictus	Eggs	min number of days for eggs development	Christophers (1960); Delatte et al. (2008)	Literature therein; La Reunion (France)	*4*	
Ae. aegypti and Ae. albopictus	Juveniles	min number of days for immature development	Christophers (1960); Delatte et al. (2008)	Literature therein; La Reunion (France)	*6*	
Ae. aegypti and Ae. albopictus	Adults	min number of days for gonotrophic cycle	Christophers (1960); Delatte et al. (2008)	Literature therein; La Reunion (France)	*4*	
Ae. koreicus and Ae. japonicus	Eggs	min number of days for eggs development	Dr Daniele Arnoldi unpublished results for *Ae. koreicus*	Trento (NE Italy)	8	
Ae. koreicus and Ae. japonicus	Juveniles	min number of days for immature development	Dr Daniele Arnoldi unpublished results for Ae. koreicus; Wieser et al. (2019)	Trento (NE Italy), Biberach (SW Germany)	9	min 10 days for *Ae. koreicus*, min 8 days for *Ae. japonicus*. Assumed 9 for both species
Ae. koreicus and Ae. japonicus	Adults	min number of days for gonotrophic cycle	Assumed the same of *Ae. aegypti*	-	4	Since the probability of complete the gonothropic cycle is roughly 1/3 of *Ae. aegypti*, we kept the same leght the same lenght of *Ae. aegypti*
All species	Juveniles	Survival rate (density-dependent)	Hancock et al. (2016)	Tropical (NE Australia)	Log-normal distribution	1-density dependant survival rate is additive to 1-temperature-dependent survial rate; the estimates made for *Ae. aegypti* were extended to the other three species
	Adults	Sex ratio 1:1	-	-	-	General modelling assumption widely taken in process-based modelling literature

Table 2: Other model features

Species	Stage	Model parameter	Data source	Origin	Function	Comments
Ae. aegypti	Egg	Survival rate	Thomas et al. (2012); Eisen et al. (2014)	Laboratory colony(Tropical Asia origin); Literature review	Beta	Data for T>0 taken from Eisen et al. (2014), data for T<0 taken from Thomas et al. (2012)
		Hatching rate	Christophers (1960); Farnesi et al. (2009); Mohammed and Chadee (2011)	Literature therein; Rockfeller strain; Trinidad and Tobago	Beta	48h estimates from Mohammed and Chadee (2011), divided by two to get a daily rate. Additional data: 0 hatching a 7°C from Christophers (1960) and 0.025 at 12°C daily hatching from Farnesi et al. (2009)
	Juvenile	Survival rate (temperature-dependent)	Yang et al. (2009)	NW of São Paulo State (Brazil)	Beta	Table 8 from Yang et al. (2009) Appendix1
		Emergence rate	Yang et al. (2009); Grech et al. (2015)	NW of São Paulo State (Brazil); Cordoba (Argentina)	Beta	Data from Yang et al. (2009) refer to all immature stages, we corrected them to match only pupa using information present in Grech et al. (2015) by taking the ratio between the minimum pupation time of the two experiment as a scaling factor
	Adult	Survival rate	Yang et al. (2009)	NW of São Paulo State (Brazil)	Beta	Table 4
		Gonotrophic cycle	Yang et al. (2009)	NW of São Paulo State (Brazil)	Beta	Table 5
		Oviposition: number of eggs	Christophers (1960); Yang et al. (2009)	Literature therein; NW of São Paulo State (Brazil)	Beta	Table 5 from Yang et al. (2009) rescaled using the average number of eggs/female reported in Christophers (1960).
Ae. albopictus	Egg	Survival rate (non-diapausing)	Metelmann et al. (2019); Expert based	Literature therein	nonlinear	Polynomial function taken from the SM manually adapted to get no survival at T>40°C
		Survival rate (diapausing)	Metelmann et al. (2019)	Literature therein	nonlinear	Polynomial function taken from the SM
		Hatching rate ((non-diapausing)	Delatte et al. (2008)	La Reunion (France)	Beta	Table 1; column Egg-L1
		Hatching rate (diapausing)	-	-	-	Assumed the same as for non-diapausing eggs
	Juvenile	Survival rate (temperature-dependent)	Metelmann et al. (2019)	Literature therein	nonlinear	Polynomial function taken from the SM
		Emergence rate	Delatte et al. (2008)	La Reunion (France)	Beta	Table 1; column Pupae-adult
	Adult	Survival rate	Metelmann et al. (2019)	Literature therein	nonlinear	Polynomial function taken from the SM
		Gonotrophic cycle	Delatte et al. (2008)	La Reunion (France)	Beta	Table 6

Species	Stage	Model parameter	Data source	Origin	Function	Comments
Ae. japonicus	Egg	Oviposition: number of eggs	Delatte et al. (2008)	La Reunion (France)	Beta	Table 6
		Survival rate	Wieser et al. (2019)	Biberach (SW Germany)	Beta	Observation taken from Fig. 1 in Wieser et al. (2019)
		Hatch rate	Wieser et al. (2019)	Biberach (SW Germany)	Beta	Reuss et al., unpublished. Hatching observed also below a thin ice layer (T<0)
	Juvenile	Survival rate	Wieser et al. (2019)	Biberach (SW Germany)	Beta	Reuss et al., unpublished
		Emergence rate	Reuss et al. (2018) Suppl. Mat.	Biberach (SW Germany)	Beta	Table S2; survival upper temperature limit was adapted by accounting for expert opinion.
	Adult	Survival rate	Reuss et al. (2018) Suppl. Mat.	Biberach (SW Germany)	Beta	Fig. 2
		Gonotrophic cycle	-	-	Beta	No information available, assumed the same of Ae. koreicus due to their phylogenetic and biogeographic similarity
		Oviposition: number of eggs	Reuss et al. (2018)	Biberach (SW Germany)	Beta	Number of eggs estimated by mean female wing length, using the formula taken from Armistead et al. (2008), their Fig. 5; we divided the estimated eggs per female per gonotrophic cycle by a factor of two, due the two ovipositing days we are accounting in the model.
Ae. koreicus	Egg	Survival rate	Marini et al. (2019b); Expert Based	Trento (NE Italy)	nonlinear	Polynomial function F3 and parameters values taken from Tab. 5 in Marini et al. (2019b) adjusted using observations provided in Arnoldi et al., unpublished observations
		Hatching rate	Marini et al. (2019b); Expert Based	Trento (NE Italy)	Beta	Table 1 scaled with unpublished data to account for non-embryonated eggs; Arnoldi et al., unpublished observations
	Juvenile	Survival rate (temperature-dependent)	Marini et al. (2019b); Expert Based	Trento (NE Italy)	Beta	Table 1 averaged from instar 1 to 4; the the upper limit has been adapted accordingly to expert opinions by Ciocchetta et al., unpublished observations and Arnoldi et al., unpublished observations
		Emergence rate	Marini et al. (2019b)	Trento (NE Italy)	Beta	Table 2
	Adult	Survival rate	Marini et al. (2019b); Expert Based	Trento (NE Italy)	Beta	Table 3
		Gonotrophic cycle	Marini et al. (2019b)	Trento (NE Italy)	Beta	Table 3
		Oviposition: number of eggs	Expert Based	Trento (NE Italy)	Beta	Arnoldi et al., unpublished observations

Table 3: Species-specific temperature-dependent physiological parameters

Species	**Stage**	**Parameters**	**Main source**	**Origin**	**Distribution**	**Comments**
Ae. aegypti	Adults	Active dispersal	Marcantonio et al. (2019)	California (USA)	Log-normal	Table 3
Ae. albopictus	Adults	Active dispersal	Marini et al. (2019a)	Rome (Italy)	Log-normal	Figure 2a; Data from the 3 MRR were fit with several distributions, best distribution chosen using AIC
Ae. japonicus	Adults	Active dispersal	-	-	Log-normal	No information available, assumed the same of *Ae. albopictus*
Ae. koreicus	Adults	Active dispersal	-	-	Log-normal	No information available, assumed the same of *Ae. albopictus*
	All species	Passive dispersal (average trip distance)	Pasaoglu et al. (2012)	-	-	Trip distance weighted average for ITA, DEU, FRA, ESP, POL, UK. Data taken from Figure 4.4 Average trip distance (km) by trip purpose using WebPlotDigitalizer
All species	Adults	Passive dispersal (Hitchhiking probability)	Eritja et al. (2017)	Mediterranean (Catalonia, Spain)	gamma distribution	0.0051 probability of a female mosquito to enter a car; Assumed to be the same for all the species as estimated by Eritja et al. (2017) for *Ae. albopictus*

Table 4: Species specific dispersal parameters

Species	**Stage**	**Model parameter**	**Data source**	**Origin**	**Function**	**Comments**
Ae. aegypti	Diapause Egg	Diapause incidence	Lacour et al. (2015)	Ovitraps (Provence, Southern France)	Exponential	
Ae. japonicus	Diapause Egg	Diapause incidence	Krupa et al. (2021)	Ovitraps (Bas-Rhin, Northeast France)	Exponential	
Ae. koreicus	Diapause Egg	Diapause incidence	Krupa et al. (2021)	Ovitraps (Bas-Rhin, Northeast France)	Exponential	We used the same exponential function used for *Ae. japonicus* due to the close philogenetic relationship between these two species

Table 5: Species specific photoperiod parameters

3 Model core equations

The core set of equations that determine the size and dynamics of egg (E), juvenile (J) and adult (F) compartments in cell s, day t is:

$$E_{s,t} = E_{s,t}^{laid} + E_{s,t}^{survive} - E_{s,t}^{hatch} \tag{1}$$

$$J_{s,t} = E_{s,t}^{hatch} + J_{s,t}^{survive} - J_{s,t}^{emerge} \tag{2}$$

$$F_{s,t} = \frac{J_{s,t}^{emerge}}{2} + F_{s,t}^{survive} \tag{3}$$

The components of equations 2-4 can be synthetically described as:

$$E_{s,t}^{laid} \sim \sum_{F_{s,t}^{lay}} Poisson(\boldsymbol{R_E}) \tag{4}$$

Where $\boldsymbol{R_E}$ is a vector of number of eggs of length s in day t derived from a temperature-dependent function. $F_{s,t}^{lay}$ correspond to adult females which have matured eggs and can lay eggs for 2 days in a row.

$$E_{s,t}^{survive} \sim Binomial(E_{s,t-1}, \boldsymbol{\Pi_{Es}}) \tag{5}$$

Where $\boldsymbol{\Pi_{Es}}$ is a vector of length s containing the probabilities of egg survival in day t derived from a temperature-dependent function.

$$E_{s,t}^{hatch} \sim Binomial(E_{s,t-1}^{survive}, \boldsymbol{\Pi_{Eh}}) \tag{6}$$

Where $\boldsymbol{\Pi_{Eh}}$ is a vector of length s containing the probabilities of egg hatching in day t derived from a temperature-dependent function.

$$J_{s,t}^{survive} \sim Multinomial(J_{s,t-1}, \boldsymbol{\Pi_{Js}}) \tag{7}$$

Where $\boldsymbol{\Pi_{Js}}$ is a vector of length s containing the probabilities of juvenile survival in day t derived from the combination of temperature-dependent and density-dependent functions.

$$J_{s,t}^{emerge} \sim Multinomial(J_{s,t-1}, \boldsymbol{\Pi_{Je}}) \tag{8}$$

Where $\boldsymbol{\Pi_{Je}}$ is a vector of length s containing the probabilities of adult emergence in day t derived from a temperature-dependent function.

$$F_{s,t}^{survive} \sim Binomial(F_{s,t-1}, \boldsymbol{\Pi_{Fs}}) \tag{9}$$

Where $\mathbf{\Pi}_{\boldsymbol{Fs}}$ is a vector of length s containing the probabilities of adult survival in day t derived from a temperature-dependent function.

4 *Aedes sp.* response curve

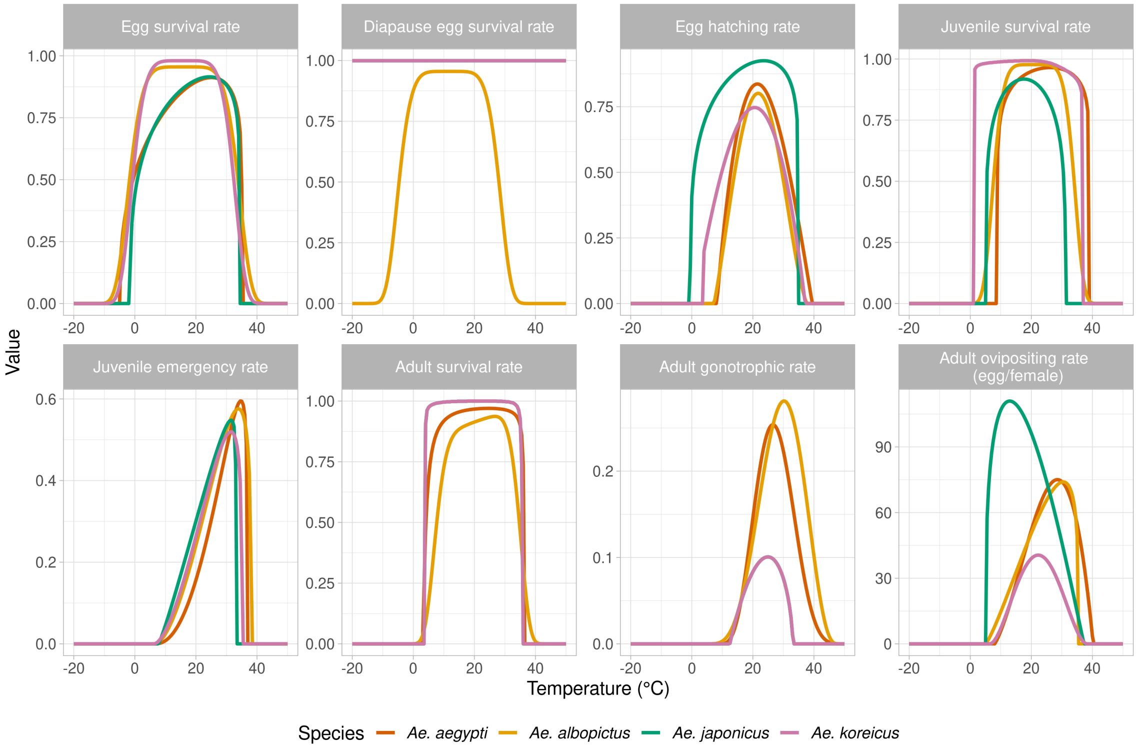

Figure 1: Overview of the temperature-dependent functions used in the model for the four *Aedes species*

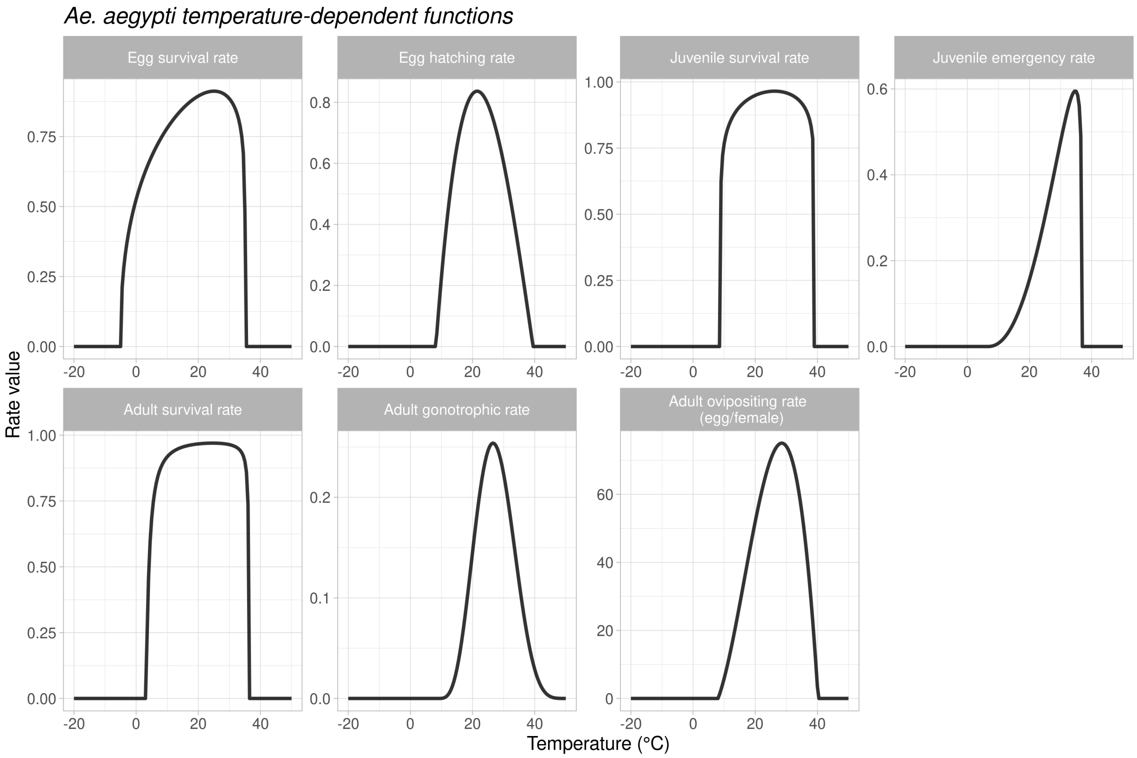

Figure 2: Overview of the temperature-dependent functions used in the model for *Ae. aegypti*

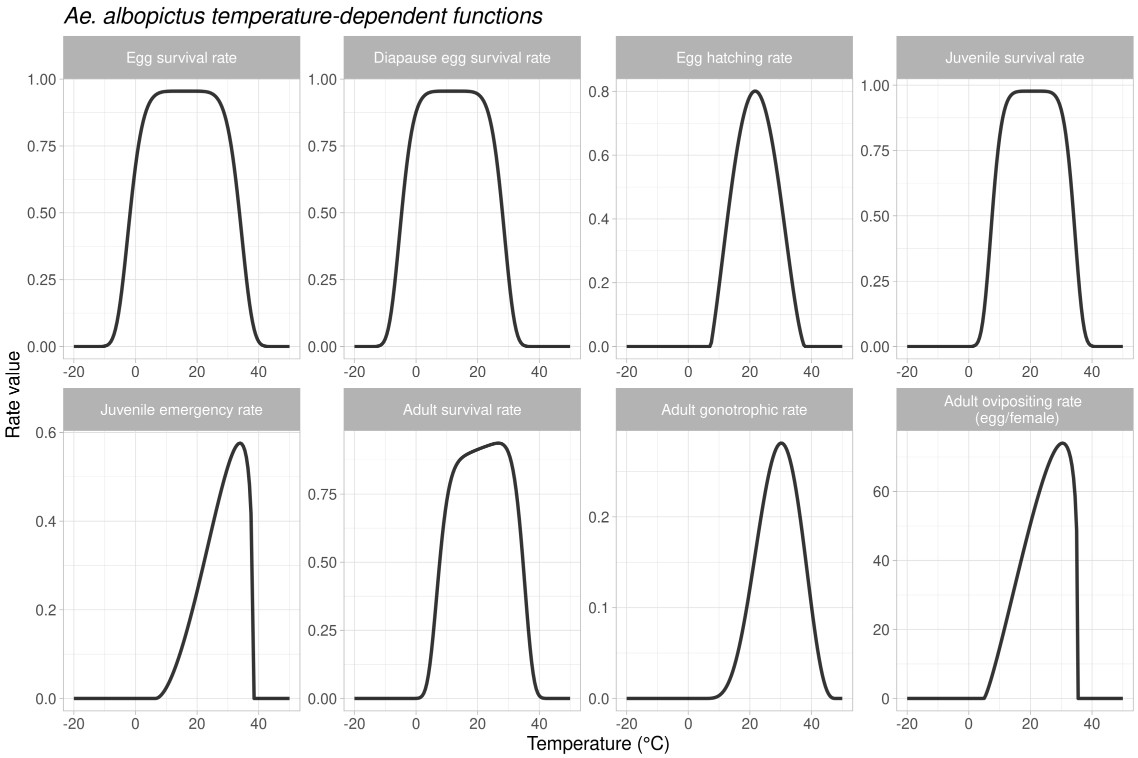

Figure 3: Overview of the temperature-dependent functions used in the model for *Ae. albopictus*

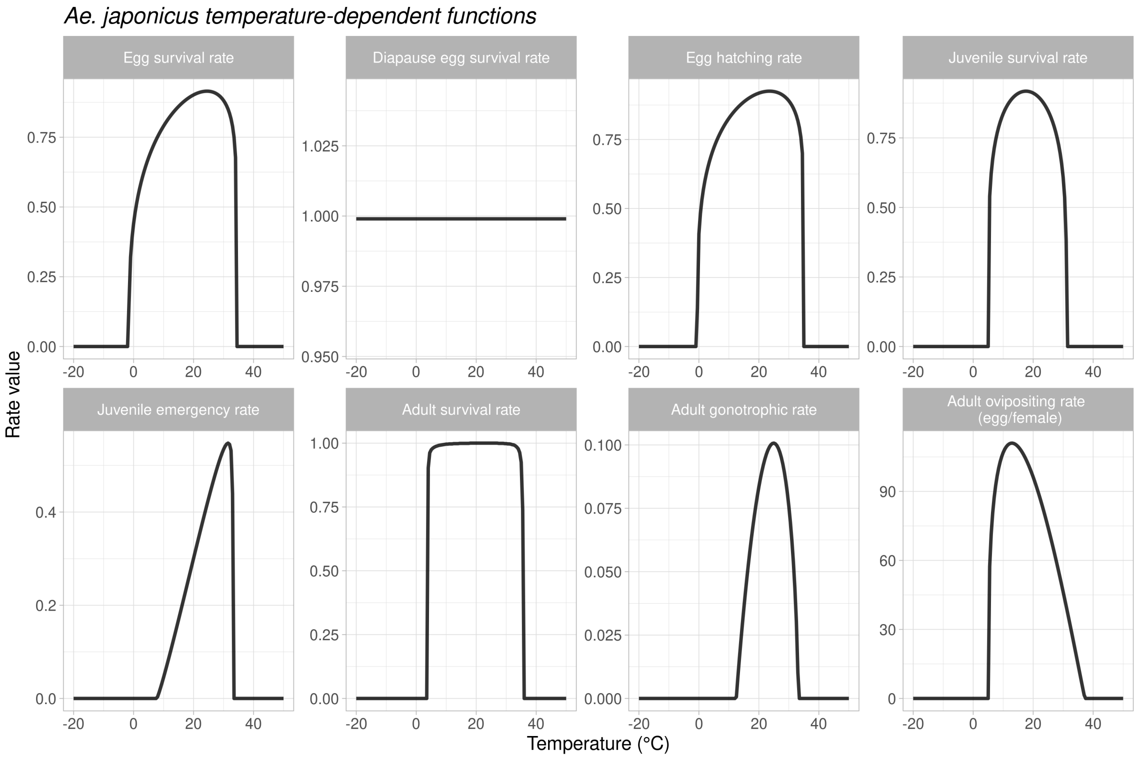

Figure 4: Overview of the temperature-dependent functions used in the model for *Ae. japonicus*

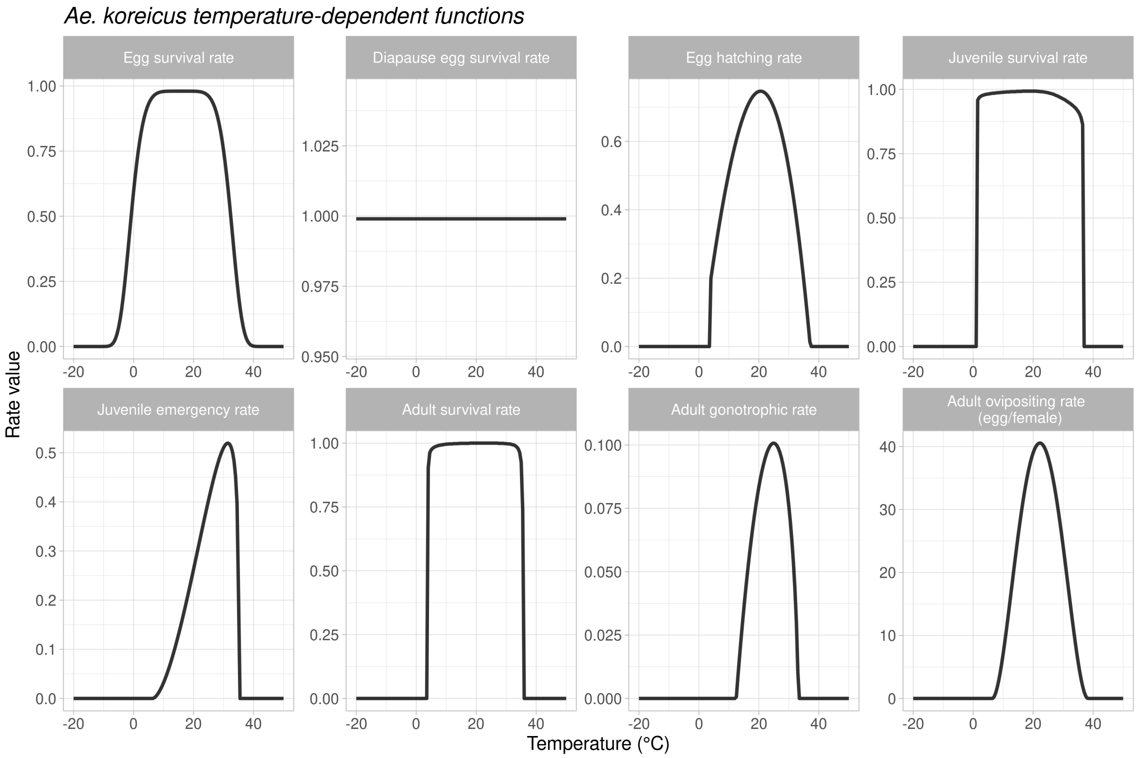

Figure 5: Overview of the temperature-dependent functions used in the model for *Ae. koreicus*

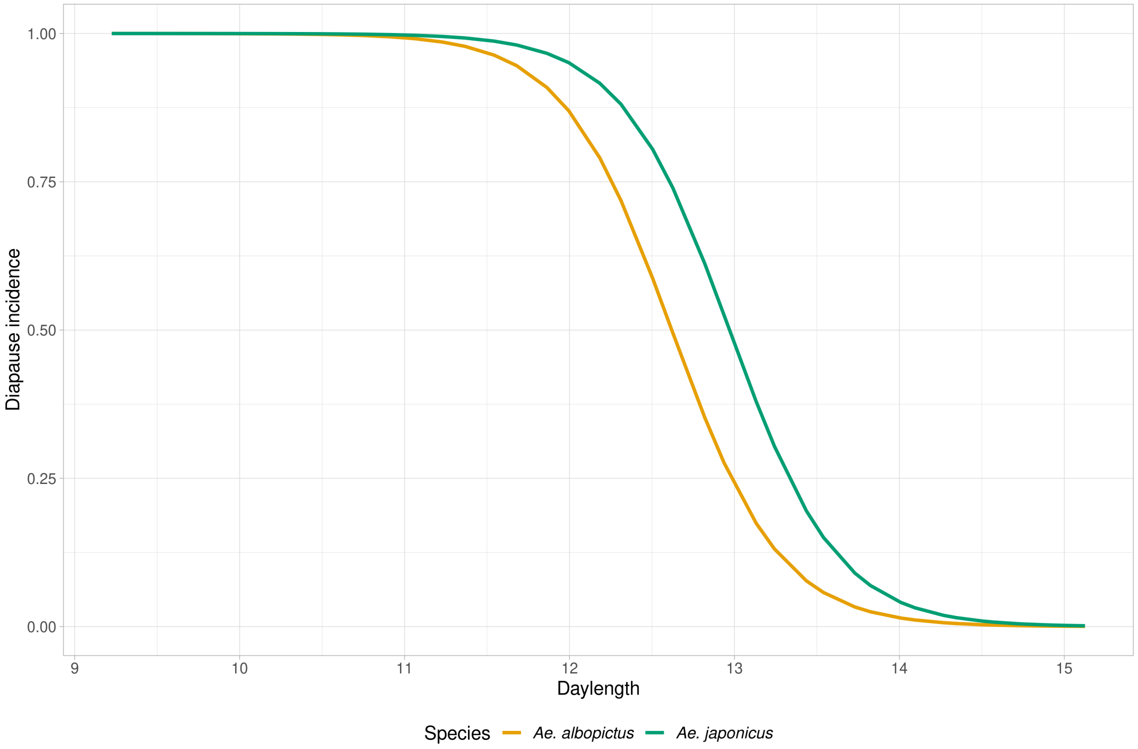

Figure 6: Overview of the photoperiod-dependent diapause incidence function used to in the model for *Ae. albopictus* and *Ae. japonicus*. The *Ae. japonicus* function was used for *Ae. koreicus* as well.

5 Juvenile-habitat water volume parameter sensitivity

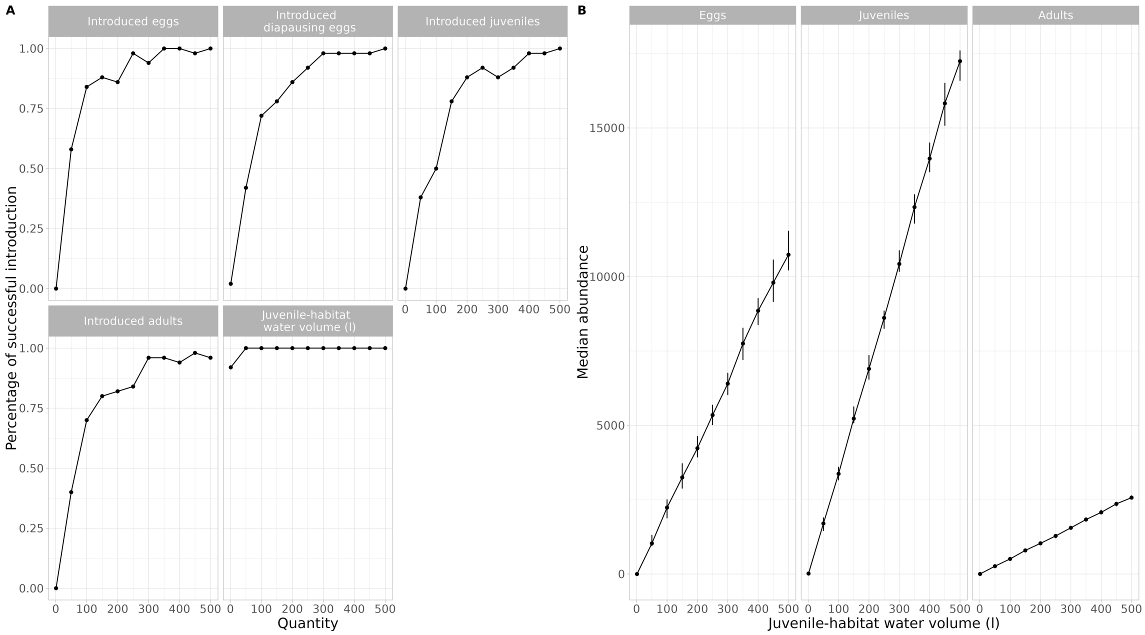

Figure 7: Sensitivity analysis on the effect of A) the variability of introduced propagules and juvenile-habitat water volume on the Percentage of successful introduction, B) the variability of the juvenile-habitat water volume on the median individual abundance.

6 *Aedes aegypti* and *Ae. albopictus* regional scale case study

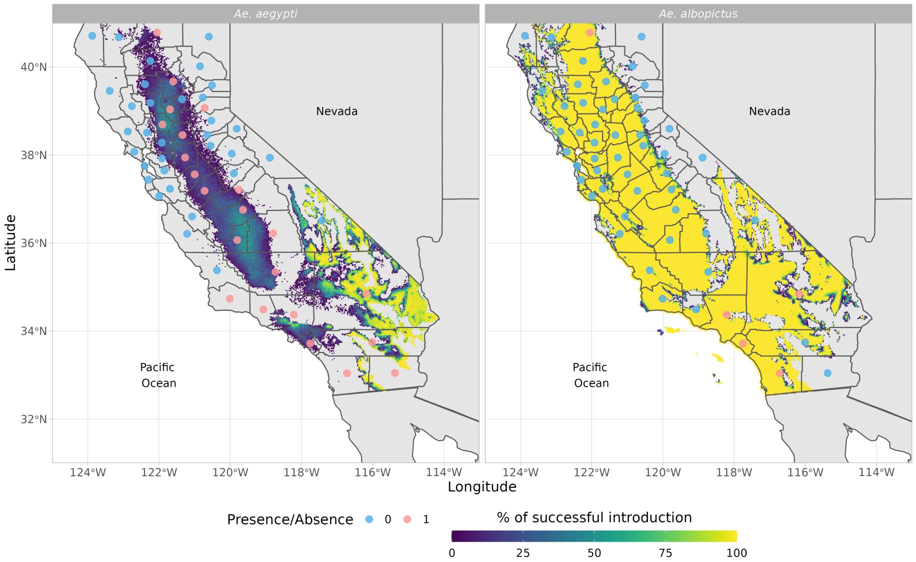

Figure 8: Predicted percentage of establishment of *Ae. aegypti Ae. albopictus* in California (USA) for the years 2011-2016 and 2013-2018, respectively. Only pixels having a probability of successful introduction >0 are shown. The red dots represent the counties where the species have been found.

7 *Aedes koreicus* population dynamics punctual scale case study

Year	Month	CI 2.5%	CI 25%	CI 50%	CI 75%	CI 97.5%	Observed *Ae. Koreicus*
2016	May	0.00	1.45	5.26	13.74	31.22	2
2016	June	0.00	1.37	6.36	14.40	40.64	5
2016	July	0.00	2.32	11.85	32.62	101.76	3
2016	August	0.70	24.57	66.65	128.03	266.00	9
2016	September	0.18	14.52	37.37	88.27	175.66	37
2016	October	0.00	0.24	1.18	3.14	10.17	0
2017	May	0.02	0.51	2.67	7.85	18.44	9
2017	June	0.29	2.75	10.60	28.57	55.28	8
2017	July	3.67	10.91	30.62	85.53	186.93	10
2017	August	7.24	32.50	74.18	159.67	283.74	24
2017	September	0.61	8.79	31.48	88.08	156.47	2
2017	October	0.08	0.82	2.20	4.98	11.06	2
2017	November	0.00	0.00	0.00	0.00	0.14	0
2018	April	1.66	5.26	11.54	22.25	34.30	0
2018	May	1.73	3.22	5.73	9.18	13.21	1
2018	June	1.57	5.81	10.52	22.29	32.89	6
2018	July	13.74	29.99	48.04	74.34	98.01	7
2018	August	37.83	71.67	109.27	157.55	201.00	29
2018	September	54.55	82.03	112.57	147.58	179.09	24
2018	October	2.13	2.90	3.77	5.89	7.80	6
2018	November	0.00	0.00	0.00	0.08	0.15	0

Table 6: Model validation for *Aedes koreicus* model in Trento (NE Italy)

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