A generalizable tool for predicting developmental phenology for wild poikilotherms.

Morgan M. Sparks[1], Brian Z. Leavell[2], Bryan M. Maitland[1]

[1]Rocky Mountain Research Station, U.S. Forest Service, Boise, Idaho

[2] Brian's deets here

Abstract

Before exogenous feeding, poikilothermic organisms have a near mechanistic relationship between ambient temperature and developmental rates. As such, statistical models can be easily developed to predict when organisms develop. Until recently, most models only used non-variable developmental regimes making them difficult to apply to wild environments. However, the R package hatchR formalized an approach using effective values where each day is given a developmental unit, accurately predicting developmental phenology for wild poikilotherms. hatchR was developed specific to fish, however this manuscript broadens the tool's application showing how it can be used to predict developmental phenology for a broad range of taxa, including amphibians, reptiles, and invertebrates. Moreover, we provide numerous examples of how this approach informs scenarios from applied management to basic questions regarding ecological and evolutionary questions.

Introduction

P1: Poikilotherms and ambient temperatures

P2: ATU models and effective value models

P3: Examples with other species

P4: Our approach here (R package and Shiny app)

Methods

Effective value models

Effective value models function by leveraging the statistical relationship derived from raising poikilotherms at different temperatures and fitting that relationship with a non-linear model. The formulation of that relationship can then be reciprocated which provides the unit of development for a day's average temperature– an effective value. Effective value models function then by cumulatively summing to one at which the organism achieves the development of the parameterized trait.

The model follows the general format of:

$$EffectiveValue_i = 1/exp(log_e a - log_e(Temperature_i - b))$$

Where i is the daily value and a fish hatches or emerges when the cumulative sum reaches one:

$$\sum_{i=1}^{n} EffectiveValue_i = 1$$

As an example, we parameterize an effective value model for coastal tailed frogs (*Ascaphus truei*) common to western North America (Figure 1). Custom parameterized models use the `fit_model()` function in hatchR, which is built on model 2 using the power law from Beacham & Murray (1990). Alternatively, to predict phenology using hatchR, the `predict_phenology()` only requires a model expression as input and could assume other model formulations custom built outside of the package by the user.

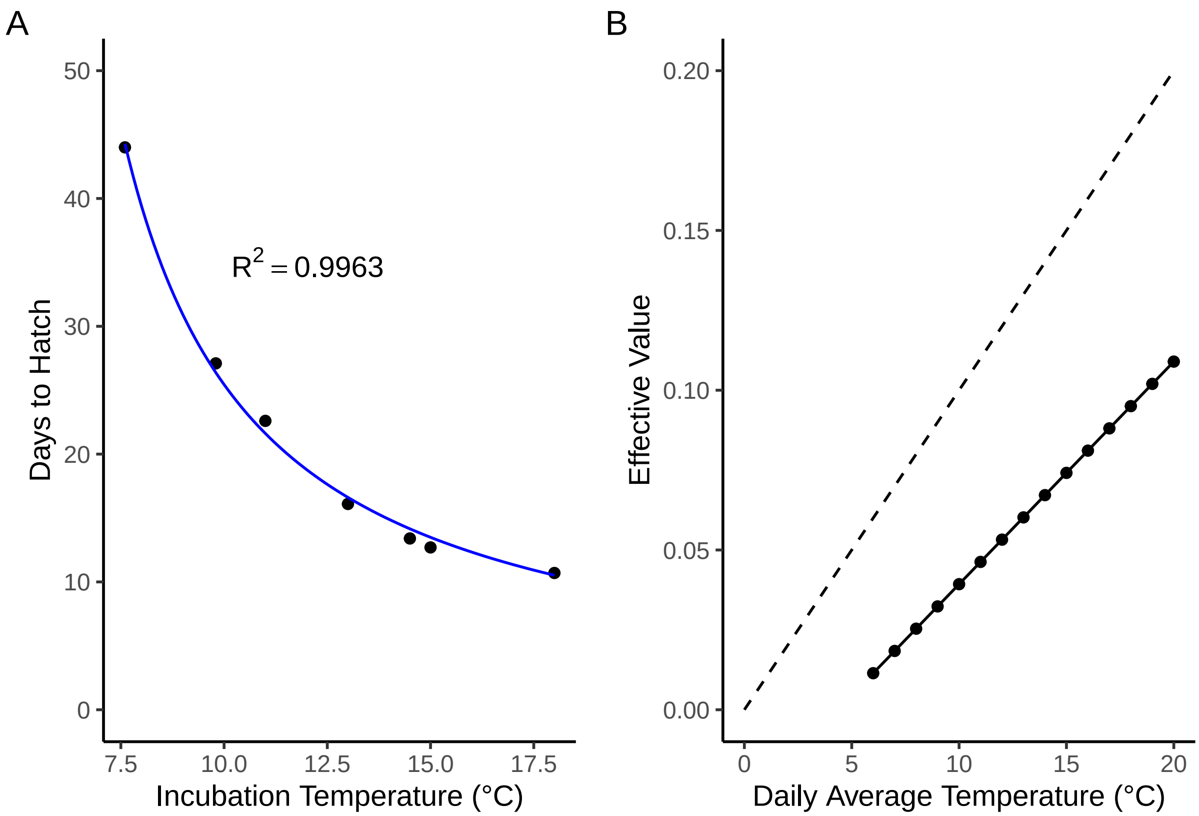

Figure 1: Custom hatching phenology model for coastal tailed frogs (Ascaphus truei).Panel A represents the model fit and raw data used to generate the effective value model and panel B are the effective values for daily temperatures between 6 and 20 °C. A dashed line with a 0.01 increase for every degree increase in included for reference.

Data and data checks

hatchR requires two essential paired vectors of data, one of daily average temperature and the other the date for those temperatures. The software is designed to function around common field temperature loggers and provides users the ability to summarize temperatures with multiple daily recordings.

Data input

Maybe include the below:

Table 1: Example temperature data for use in hatchR.

date	temperature
2024-01-01	4.67
...	...
2024-07-01	22.31
...	...
2024-12-31	2.58

If you import data from raw files with multiple daily readings, the package allows you to summarize your with `summarize_temp()` and then check summarized data with the `plot_check_temp()` and `check_continuous()` functions.

Predicting phenology

hatchR has two function to predict phenology. The first is `predict_phenology()` where users input date of reproductive event (`spawn.date`) along with their daily average temperature and corresponding dates. Alternatively, the function `predict_spawn()` leverages the effective value model framework but works backward from observed or expected development. For example, if a user observed one of the many frog or reptile parameterizations below in an area where they had accurate temperature measurements, they could easily estimate when those individuals' adults mated.

Case studies

There are numerous applications for effective value models and poikilotherms that expand well beyond the bounds of this manuscript. We provide examples spanning four taxonomic classes of pikilotherms in the table below of studies that could liekly be used to parameterize custom models using the `fit_model()` function from hatchR. These are a non-exhaustive search of the both peer-reviewed and grey literature, but demonstrate the wide taxonomic breadth that could be paired with the effective value approach. We provide case studies of how these data may be used to address a variety of questions, but expect applications to extend far beyond what we demonstrate here.

Table 2: Sources for effective value parameterizations using `fit_model()` in hatchR. Represented are a broad range of taxa and some review studies which include numerous putative sources. While et al. (2018) and Pritchard & Leggott (1987) not vetted for full functionality and equations would need to be reciprocated.

Class	Order	Genera	Species	Study
Amphibia	Anura	*Lithobates*	*L. sylvaticus*	Moore (1939)
			L. pipiens	
			L. clamitans	
			L. palustris	
		Ascaphus	*A. truei*	Herbert A. Brown (1975)
	Urodela	*Ambystoma*	*A. gracile*	Herbert A. Brown (1976)
Reptilia	Squamata	*Sceloporus*	*S. undulatus*	Angilletta, Winters, & Dunham (2000)
		Podarcis	*P. mural*is	Van Damme, Bauwens, Braña, & Verheyen (1992)
	Testudines	*Mauremys*	M. reevesii	Du, Hu, Lu, & Zhu (2007)

Class	Order	Genera	Species	Study
			181 species	141 studies in While et al. (2018)
Insecta	Plecoptera	*Nemurella*	*N. pictetii*	John E. Brittain (1978), Elliott (1984)
		Capnia	*C. atra*	John E. Brittain & Mutch (1984)
		Capnia	*C. bifrons*	Elliott (1986)
		Mesocapnia	*M. oenone*	John E. Brittain & Mutch (1984)
		Taeniopteryx	*T. nebulosa*	J. E. Brittain (1977)
	Coleoptera	*Colaphellus*	*C. bowringi*	Tang, He, Chen, Fu, & Xue (2017)
			18 species	Developmental equations in Pritchard & Leggott (1987)
Malacostraca	Decapoda	*Pontastacus*	*P. leptodactylus*	Aydın & Dilek (2004)

Ecological

Recreate Karraker et al. (2006) with data from Siegel, Fullerton, FitzGerald, Holzer, & Jordan (2023)

Phylogenetic

Frog example Moore 1939.

Pic labels are wrong, check

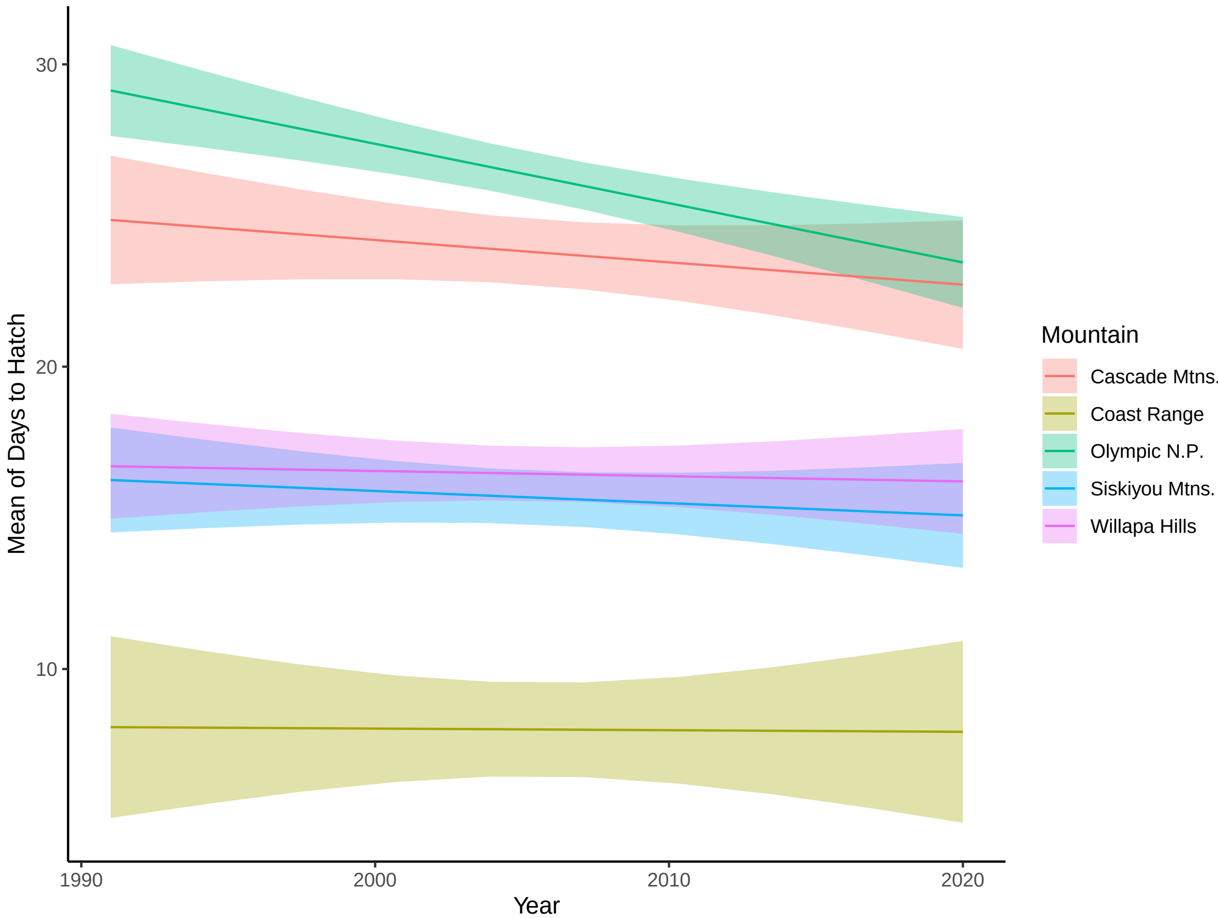

Figure 2: Estimated marginal means of days to hatch for coastal tailed frogs from various mountain ranges across their range.

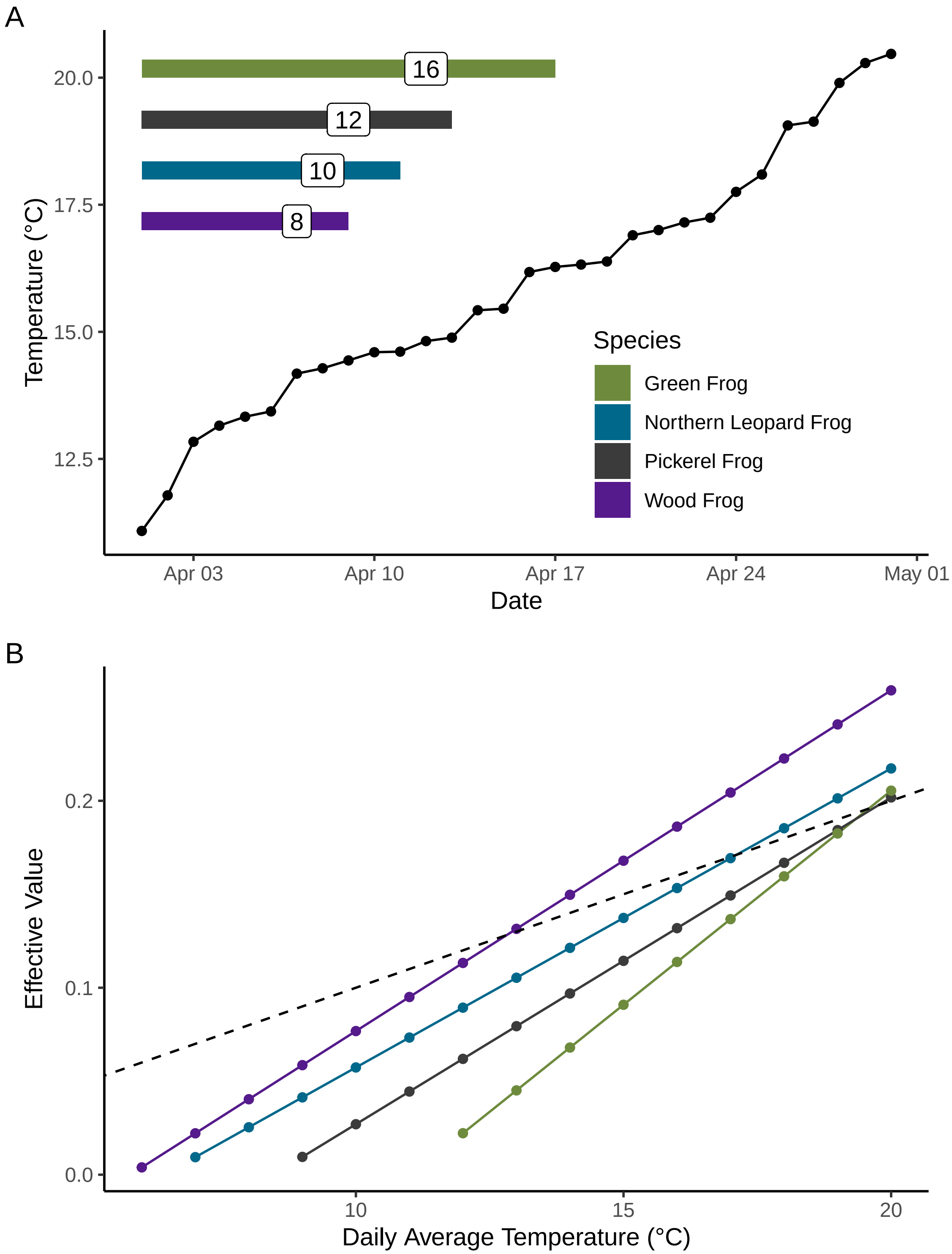

Figure 3: Custom hatch timing models developed for four North American frog species. Models are parameterized from Moore 1939 and phenology is predicted using a randomly generated temperature regime with mean 16 °C (Panel A). Panel B shows the effective values for different mean daily temperatures for each species, which are effectively species-specific linearized developmental reaction norms.

Local Adaptation

Need an example where multiple populations from the same species are parameterized. ideally not an amphibian

Tang et al. (2017) example using females

Evidence for cogradient clinal adaptation where the farthest south population develops the fastest.

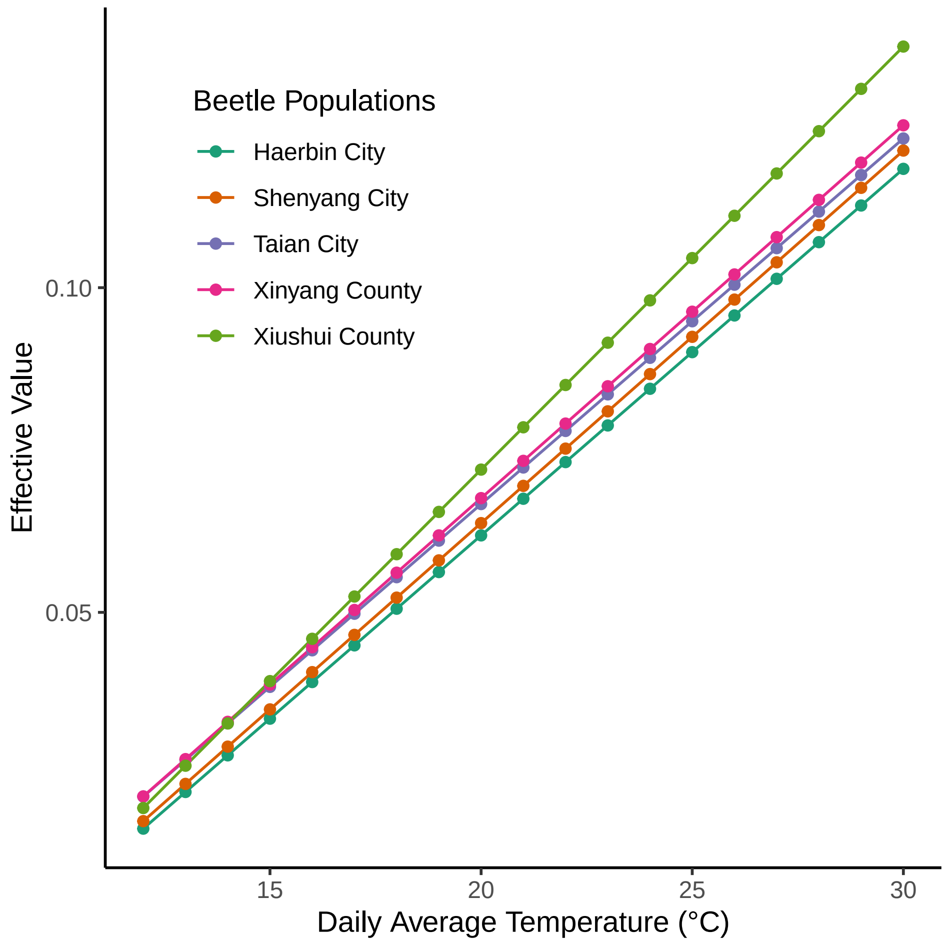

Figure 4: Effective value models developed for five populations of cabbage beetle (females) along a latitudinal cline in China from Tang et al. 2017. Note the large difference in developmental rate between Xiushui County and the other, more notherly populations, which is indicative of cogradient variation.

Discussion

P1: Summary of above

P2: Caveats

- namely that some taxa like insects and frogs are much more likely to bail on development when environmental cues suggest they need to
- more studies need to include more than 2 temperatures Qualls & Shine (1998) Kozák et al. (2009)

P3: Other considerations?

- easy to parameterize custom models for quick developing species
- examples where other stages could be modeled assuming constant feeding (Lillehammer, 1986)

P4: ???

Conclusion

Isn't this a great tool with so many applications!?

Bibliography

Angilletta, M. J., Winters, R. S., & Dunham, A. E. (2000). THERMAL EFFECTS ON THE ENERGETICS OF LIZARD EMBRYOS: IMPLICATIONS FOR HATCHLING PHENOTYPES. *Ecology*, *81*(11), 2957–2968. doi:10.1890/0012-9658(2000)081[2957:TEOTEO]2.0.CO;2

Aydın, H., & Dilek, M. K. (2004). Effects of Different Water Temperatures on the Hatching Time and Survival Rates of the Freshwater Crayfish Astacus leptodactylus (Esch., 1823) Eggs. *Turkish Journal of Fisheries and Aquatic Sciences*, *4*(2), –. Retrieved from https://dergipark.org.tr/en/pub/trjfas-ayrildi/issue/13289/160618

Beacham, T. D., & Murray, C. B. (1990). Temperature, egg size, and development of embryos and alevins of five species of pacific salmon: A comparative analysis. *Transactions of the American Fisheries Society*, *119*(6), 927–945. doi:10.1577/1548-8659(1990)119<0927:TESADO>2.3.CO;2

Brittain, J. E. (1977). The effect of temperature on the egg incubation period of taeniopteryx nebulosa (plecoptera). *Oikos*, *29*(2), 302–305. doi:10.2307/3543618

Brittain, John E. (1978). Semivoltinism in mountain populations of nemurella pictetii (plecoptera). *Oikos*, *30*(1), 1–6. doi:10.2307/3543518

Brittain, John E., & Mutch, R. A. (1984). THE EFFECT OF WATER TEMPERATURE ON THE EGG INCUBATION PERIOD OF MESOCAPNIA OENONE (PLECOPTERA) FROM THE CANADIAN ROCKY MOUNTAINS. *The Canadian Entomologist*, *116*(4), 549–554. doi:10.4039/Ent116549-4

Brown, Herbert A. (1975). Temperature and development of the tailed frog, *Ascaphus truei*. *Comparative Biochemistry and Physiology Part A: Physiology*, *50*(2), 397–405. doi:10.1016/0300-9629(75)90033-X

Brown, Herbert A. (1976). The time–temperature relation of embryonic development in the northwestern salamander, *Ambystoma gracile*. *Canadian Journal of Zoology*, *54*(4), 552–558. doi:10.1139/z76-063

Du, W.-G., Hu, L.-J., Lu, J.-L., & Zhu, L.-J. (2007). Effects of incubation temperature on embryonic development rate, sex ratio and post-hatching growth in the chinese three-keeled pond turtle, *Chinemys reevesii*. *Aquaculture*, *272*(1), 747–753. doi:10.1016/j.aquaculture.2007.09.009

Elliott, J. M. (1984). Hatching time and growth of Nemurellapictetii (Plecoptera: Nemouridae) in the laboratory and a Lake District stream. *Freshwater Biology*, *14*(5), 491–499. doi:10.1111/j.1365-2427.1984.tb00169.x

Elliott, J. M. (1986). The effect of temperature on the egg incubation period of capnia bifrons (plecoptera: Capniidae) from windermere (english lake district). *Holarctic Ecology*, *9*(2), 113–116. Retrieved from https://www.jstor.org/stable/3682086

Karraker, N. E., Pilliod, D. S., Adams, M. J., Bull, E. L., Corn, P. S., Diller, L. V., Dupuis, L. A., et al. (2006). TAXONOMIC VARIATION IN OVIPOSITION BY TAILED FROGS (ASCAPHUS SPP). *Northwestern Naturalist*, *87*(2), 87–97. doi:10.1898/1051-1733(2006)87[87:TVIOBT]2.0.CO;2

Kozák, P., Buřič, M., Kanta, J., Kouba, A., Hamr, P., & Policar, T. (2009). The effect of water temperature on the number of moults and growth of juvenile signal crayfish Pacifastacus leniusculus Dana. *Czech Journal of Animal Science*, *54*(6), 286–292. doi:10.17221/1727-CJAS

Lillehammer, A. (1986). The effect of temperature on the egg incubation period and nymphal growth of two nemoura species (plecoptera) from subarctic fennoscandia. *Aquatic Insects*, *8*(4), 223–235. doi:10.1080/01650428609361257

Moore, J. A. (1939). Temperature tolerance and rates of development in the eggs of amphibia. *Ecology*, *20*(4), 459–478. doi:10.2307/1930439

Pritchard, G., & Leggott, M. A. (1987). Temperature, incubation rates and origins of dragonflies. *Advances in odonatology*, *3*(1), 121–126. Retrieved from https://natuurtijdschriften.nl/pub/593065

Qualls, F. J., & Shine, R. (1998). Geographic variation in lizard phenotypes: importance of the incubation environment. *Biological Journal of the Linnean Society*, *64*(4), 477–491. doi:10.1111/j.1095-8312.1998.tb00345.x

Siegel, J. E., Fullerton, A. H., FitzGerald, A. M., Holzer, D., & Jordan, C. E. (2023). Daily stream temperature predictions for free-flowing streams in the Pacific Northwest, USA. *PLOS Water*, *2*(8), e0000119. doi:10.1371/journal.pwat.0000119

Tang, J., He, H., Chen, C., Fu, S., & Xue, F. (2017). Latitudinal cogradient variation of development time and growth rate and a negative latitudinal body weight cline in a widely distributed cabbage beetle. *PLOS ONE*, *12*(7), e0181030. doi:10.1371/journal.pone.0181030

Van Damme, R., Bauwens, D., Braña, F., & Verheyen, R. F. (1992). Incubation temperature differentially affects hatching time, egg survival, and hatchling performance in the lizard podarcis muralis. *Herpetologica*, *48*(2), 220–228. Retrieved from https://www.jstor.org/stable/3892675

While, G. M., Noble, D. W. A., Uller, T., Warner, D. A., Riley, J. L., Du, W.-G., & Schwanz, L. E. (2018). Patterns of developmental plasticity in response to incubation temperature in reptiles. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, *329*(4-5), 162–176. doi:10.1002/jez.2181