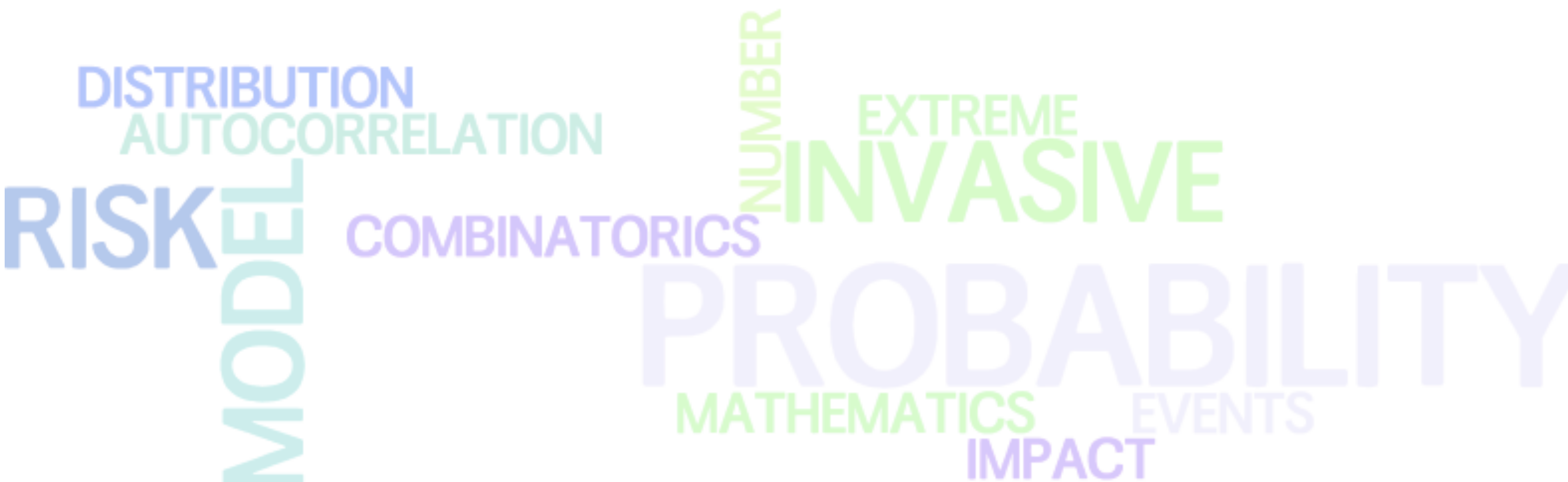
Transients, autocorrelated variation, and invasive species impact



UNIVERSITY OF WATERLOO

Kim Cuddington
ecotheory.uwaterloo.ca

How do we predict….

- If a species will persist?
- If a species will have a negative impact?
- Are these questions the same?

Common approach

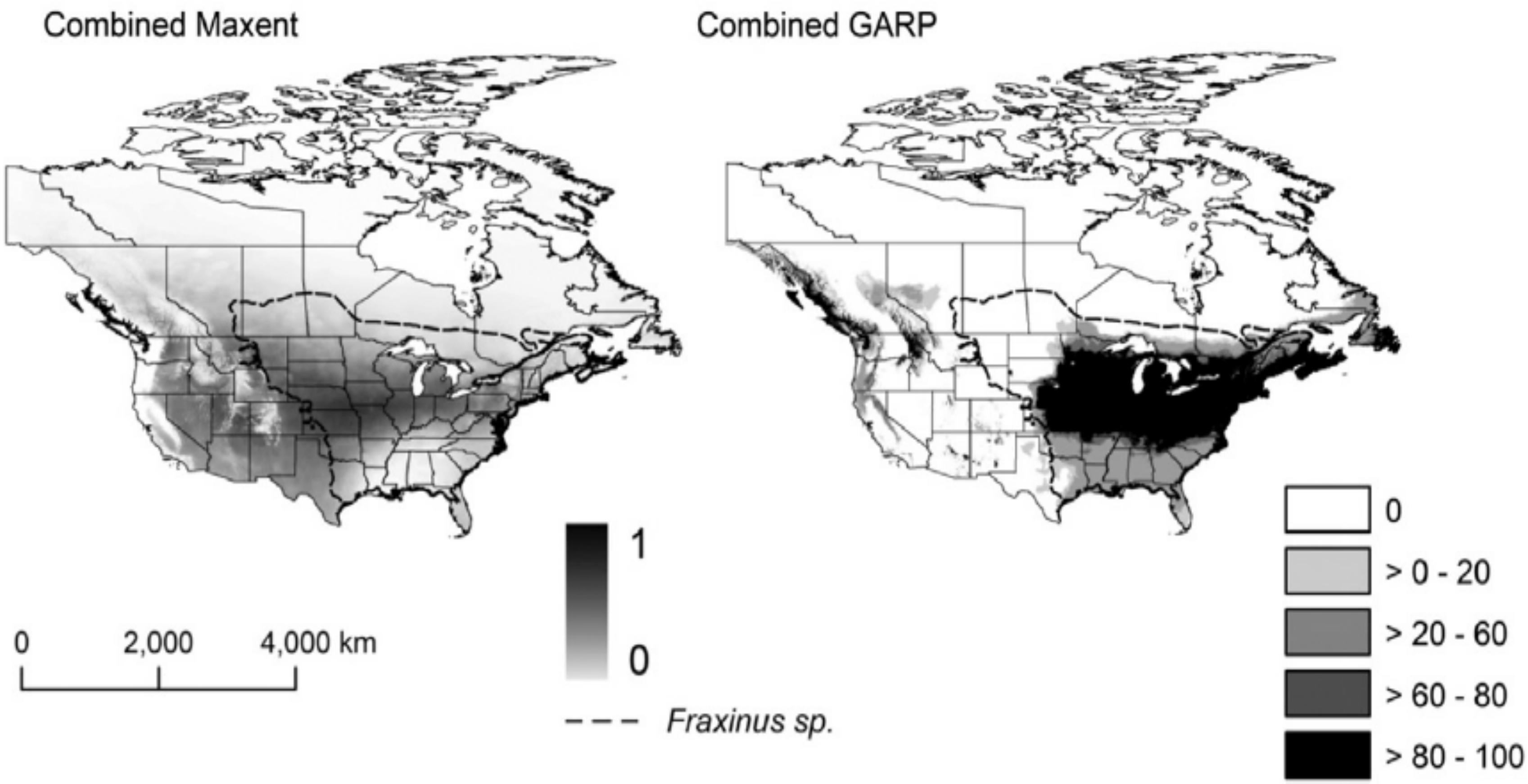
- Use climate matching to determine if species will persist in its new environment (e.g., MaxEnt)

- 1300 papers from 2018-2019

Predicting invasive species range via climate matching

- Take occurance in old range, estimate climate conditions at these locations, find similar conditions in the new range, predict occurance with some probability
- e.g., use climate variables from WorldCim
  - BIO1 = Annual Mean Temperature
  - BIO6 = Min Temperature of Coldest Month
  - BIO9 = Mean Temperature of Driest Quarter
  - BIO17 = Precipitation of Driest Quarter

Emerald Ash Borer – climate matching predictions

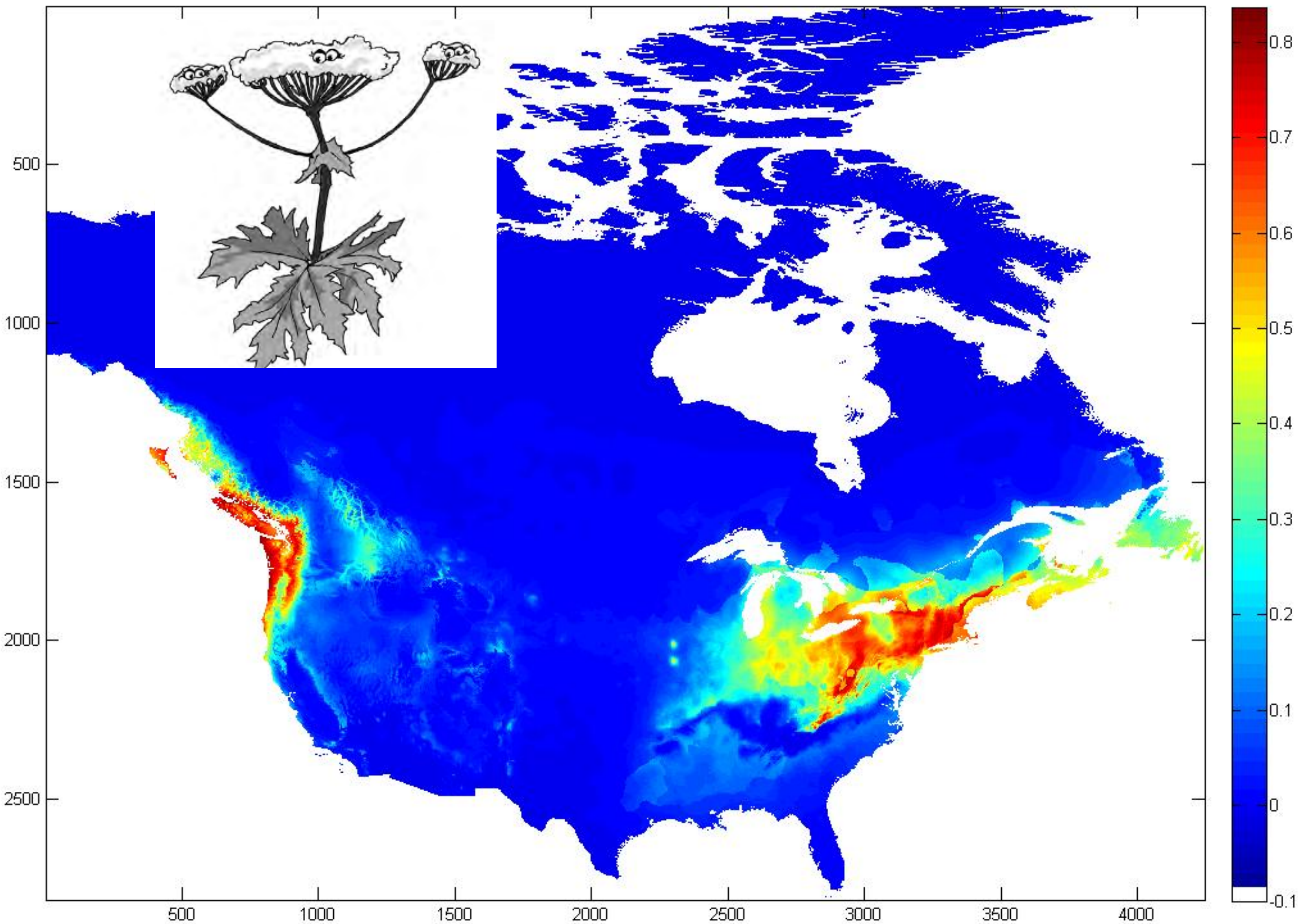


Sobek-Swant et al. (2012) Forest Ecology and Management 281: 23–31

Subtext

Potential for invasive species impact
= probability of indefinite
persistence

Habitat suitability for Giant Hogweed (hot colours=highly suitable)



Population spread & habitat model for giant hogweed

$$N_{t+1}(x,y) = \int\int f\big(N_t(u,v)\big)\, k(x-u, y-v)\,du\,dv$$

where $f\big(N_t(u,v)\big) = \lambda * hsm(u,v) * \big(N_t(u,v)\big)$

$$k(x-u, y-v) = \frac{1}{2\pi\sigma^2}\exp\left(-\frac{(x-u)^2 + (y-v)^2}{2\sigma^2}\right)$$

$\lambda = 1.2/\text{yr}$; $\sigma^2 = 1.25\ \text{km}^2/\text{yr}$

Population spread & habitat model

$$N_{t+1}(x,y) = \int\int f\big(N_t(u,v)\big)\, k(x-u, y-v)\, du\, dv$$

Annual reproduction
Continuous space

Habitat suitability
From MaxEnt model

$$\text{where } f\big(N_t(u,v)\big) = \lambda * hsm(u,v) * \big(N_t(u,v)\big)$$

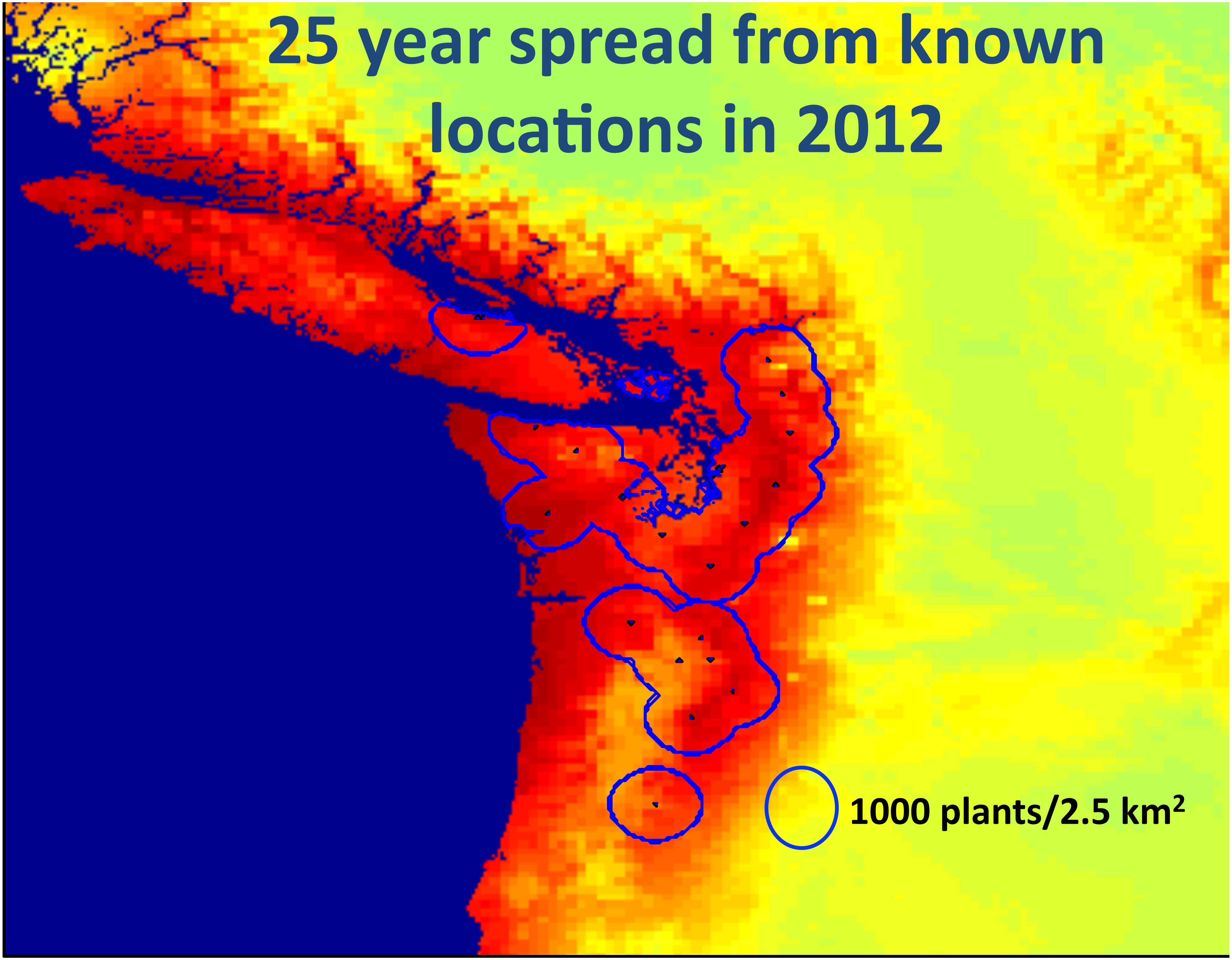
$$k(x-u, y-v) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{(x-u)^2 + (y-v)^2}{2\sigma^2} \right)$$

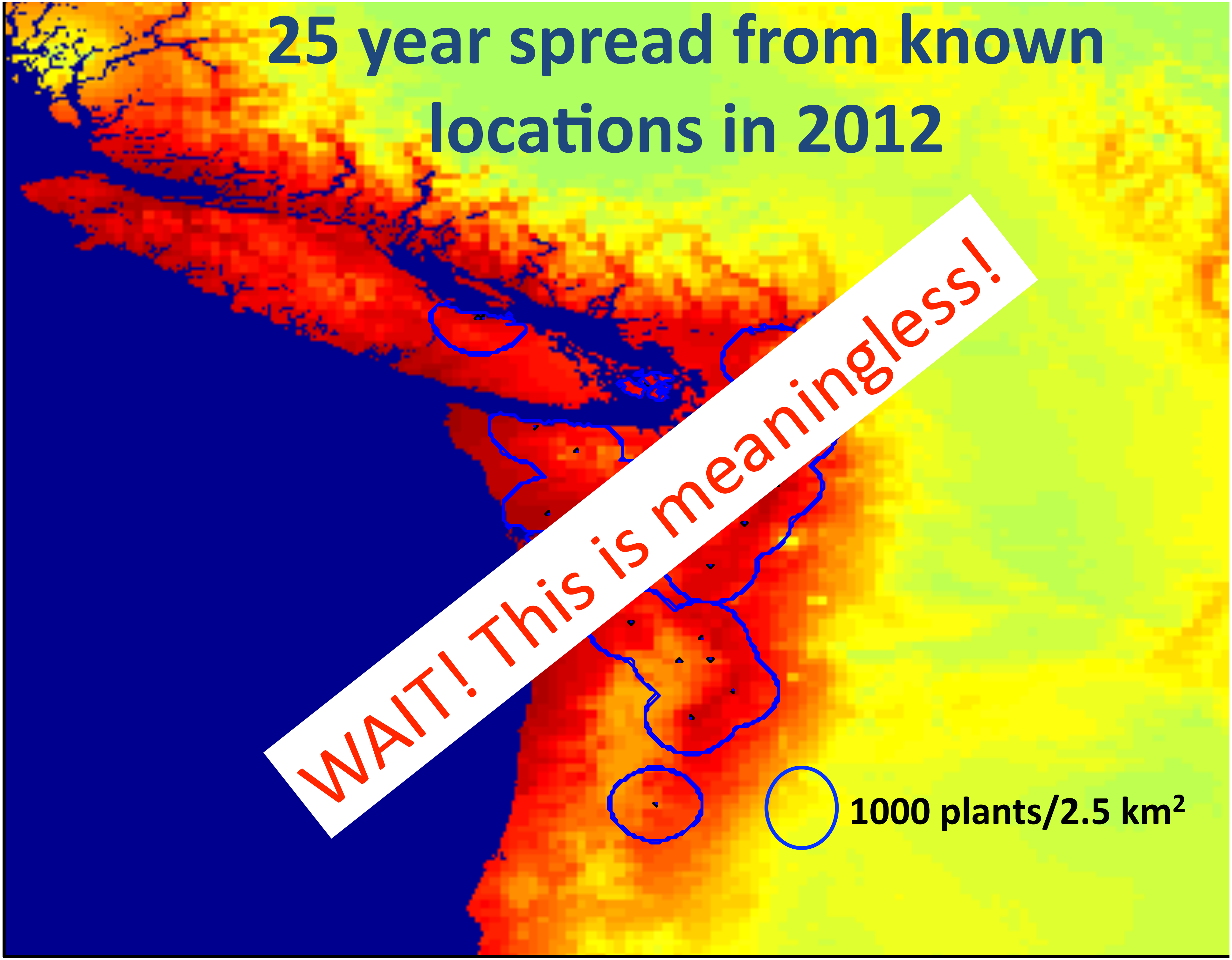
Gaussian spread

Age-structured model

Literature data

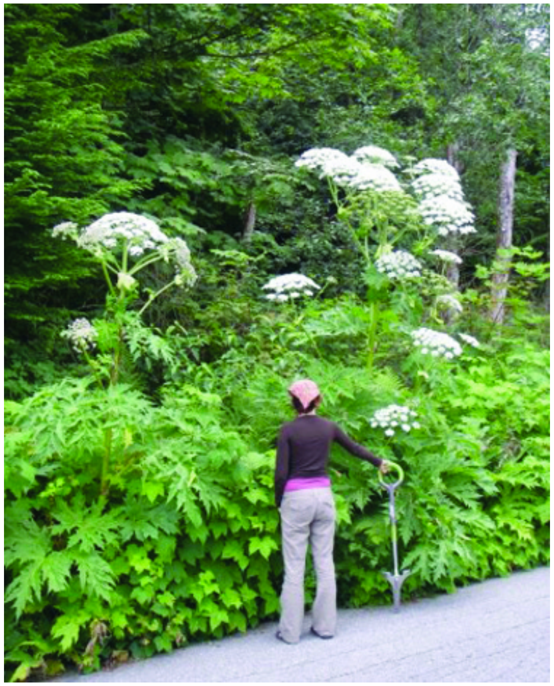
$$\lambda = 1.2/\text{yr} \; ; \qquad \sigma^2 = 1.25 \;\; \text{km}^2/\text{yr}$$


25 year spread from known locations in 2012
1000 plants/2.5 km²


25 year spread from known locations in 2012
WAIT! This is meaningless!
1000 plants/2.5 km²

Climate matching tells us nothing about mechanisms that affect growth rate or spread

And anyway, is indefinite persistence really the most important factor for potential invasive species impact?



Impact: Population size

- For example, some invasive species have no negative impacts at low density.
  - Giant Hogweed has no negative effect on the surrounding plant community until greater than 50% cover is reached (Theile et al. 2010).
  - Also has low impact on human heath until higher density in high use areas

Impact: Persistence time

- Some species may not even need to persist idenfinitely in order to have a big impact
  - EAB can kill trees in 4-6 years (Knight et al. 2013)

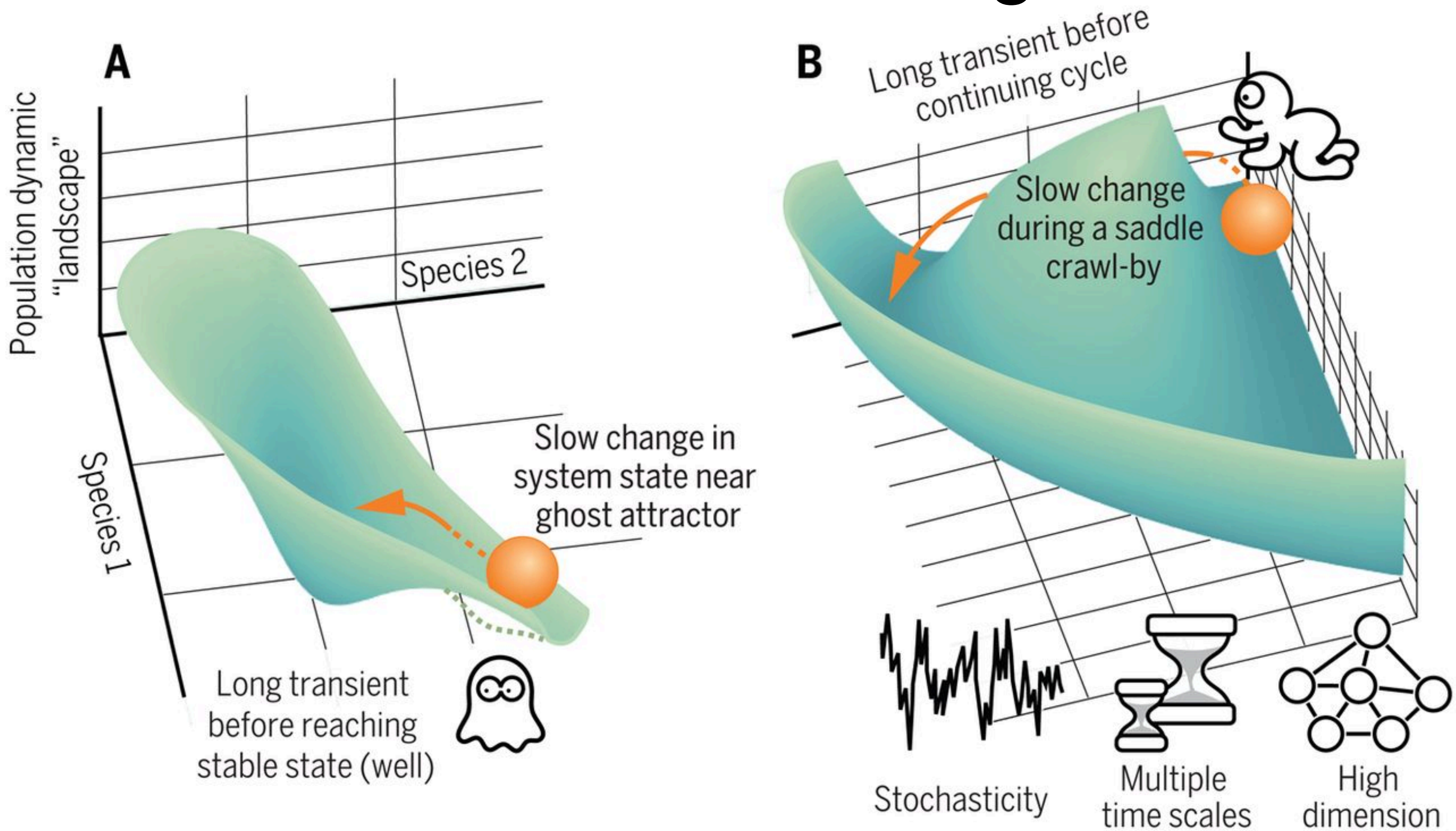
Shift in focus from predicting indefinite persistence to predicting transient conditions that may be related to impact

i.e., populations that only temporarily persist or temporarily reach large size may have meaningful risk of impact

When I think about transients, I think about….

- Internal dynamics
- External fluctuations
- Initial conditions

Long transients related to internal dynamics, illustrated as a ball rolling downhill



Hastings et al. (2018) Science 361:eaat6412

1. Just environmental variation: What is the probability of economic impact of Emerald Ash Borer (EAB) in northern cities?

Cuddington et al. (2018) Biol Invasions 20: 2661-2677

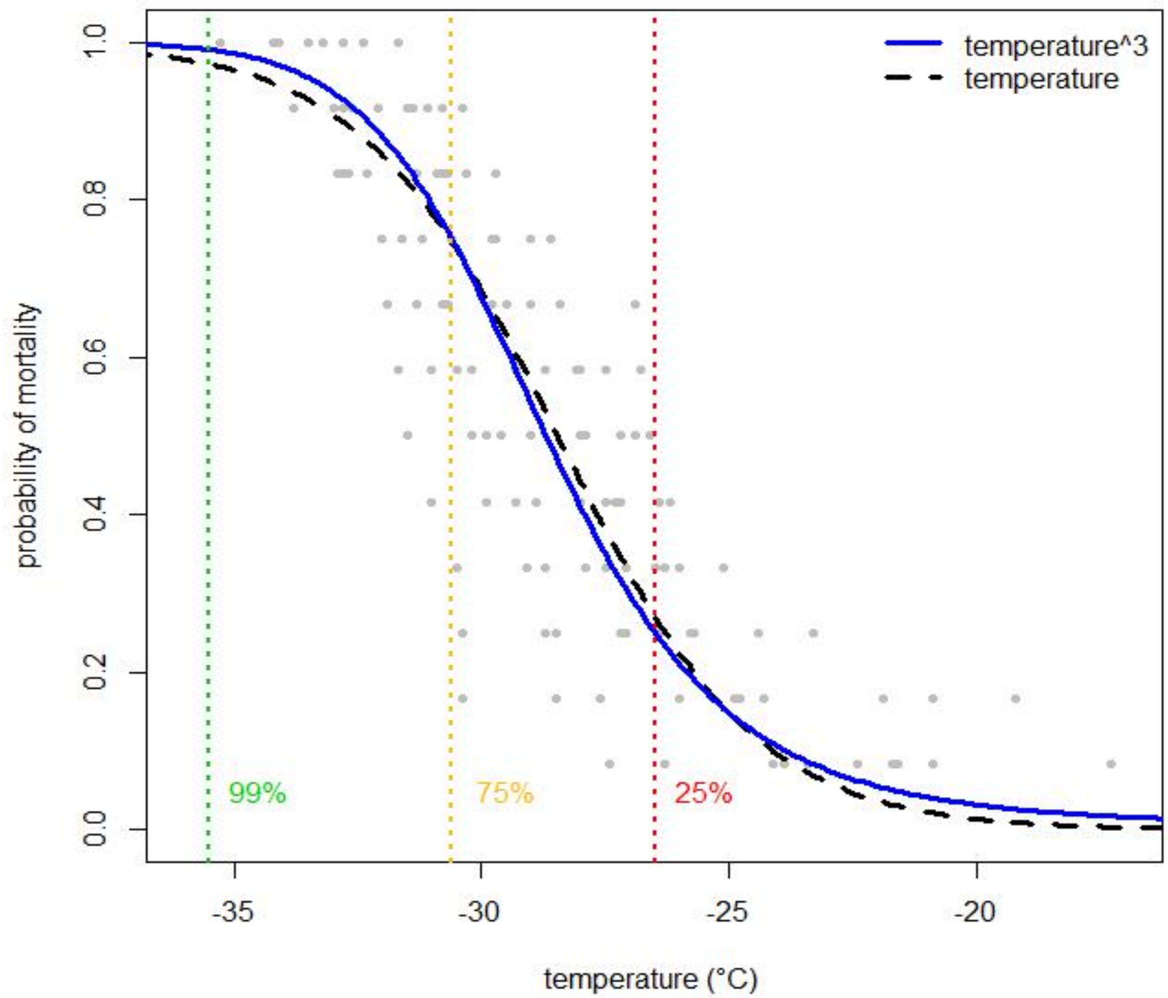
Vermunt et al. (2012) Ecological Modelling 235–236: 19–25

Sobek-Swant et al. (2012) Biol Invasions 14:115–125

Transient persistence time

- Emerald ash borer (EAB) can kill trees in 4-6 years
- What is the probability EAB will persist long enough to kills trees if it arrives in an area?

EAB mortality at cold temperatures

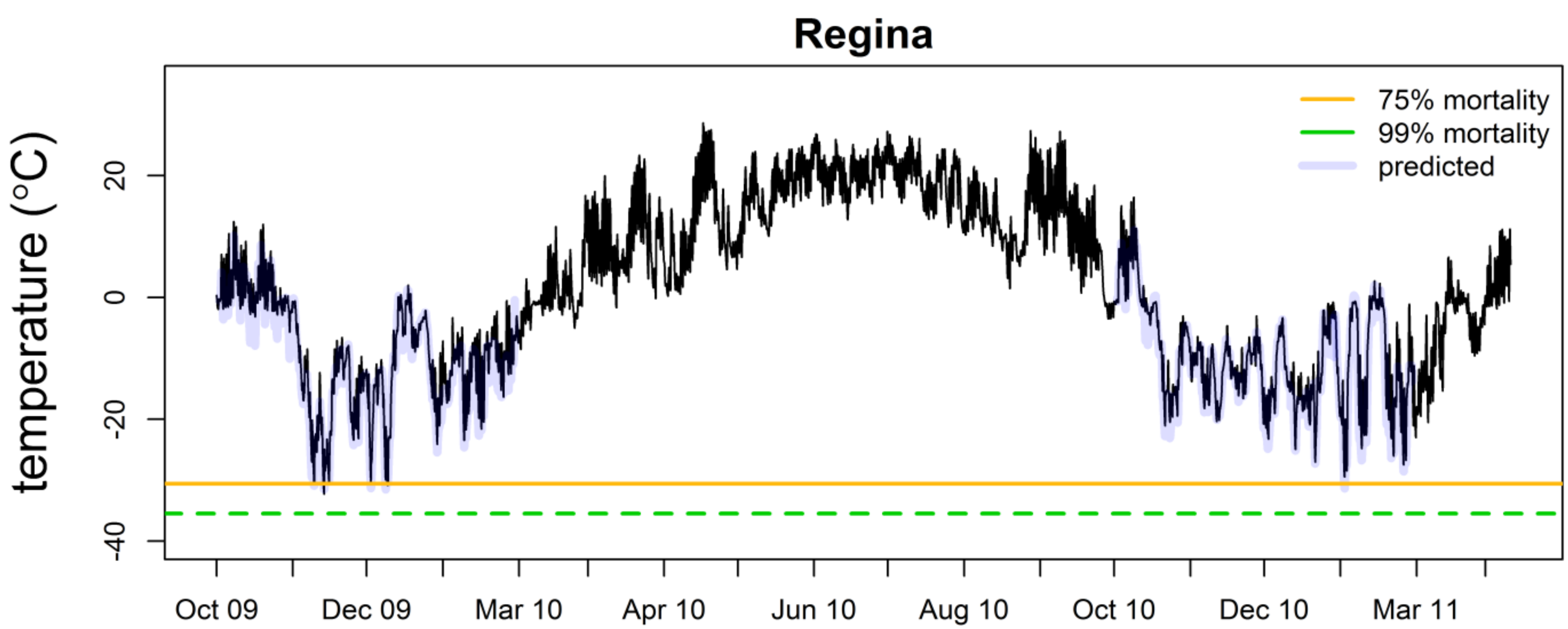


Data from Crosthwaite et al (2011) Journal of Insect Physiology 57: 166-173.

Side note: Thermal responses of ecotherms are determined by microclimate conditions

Therefore, to make predictions about temperature variation on invasive species impact we need microclimate conditions

Measured and predicted underbark temperatures (Newtonian cooling model)



Predicted min underbark temp from 1945-2012

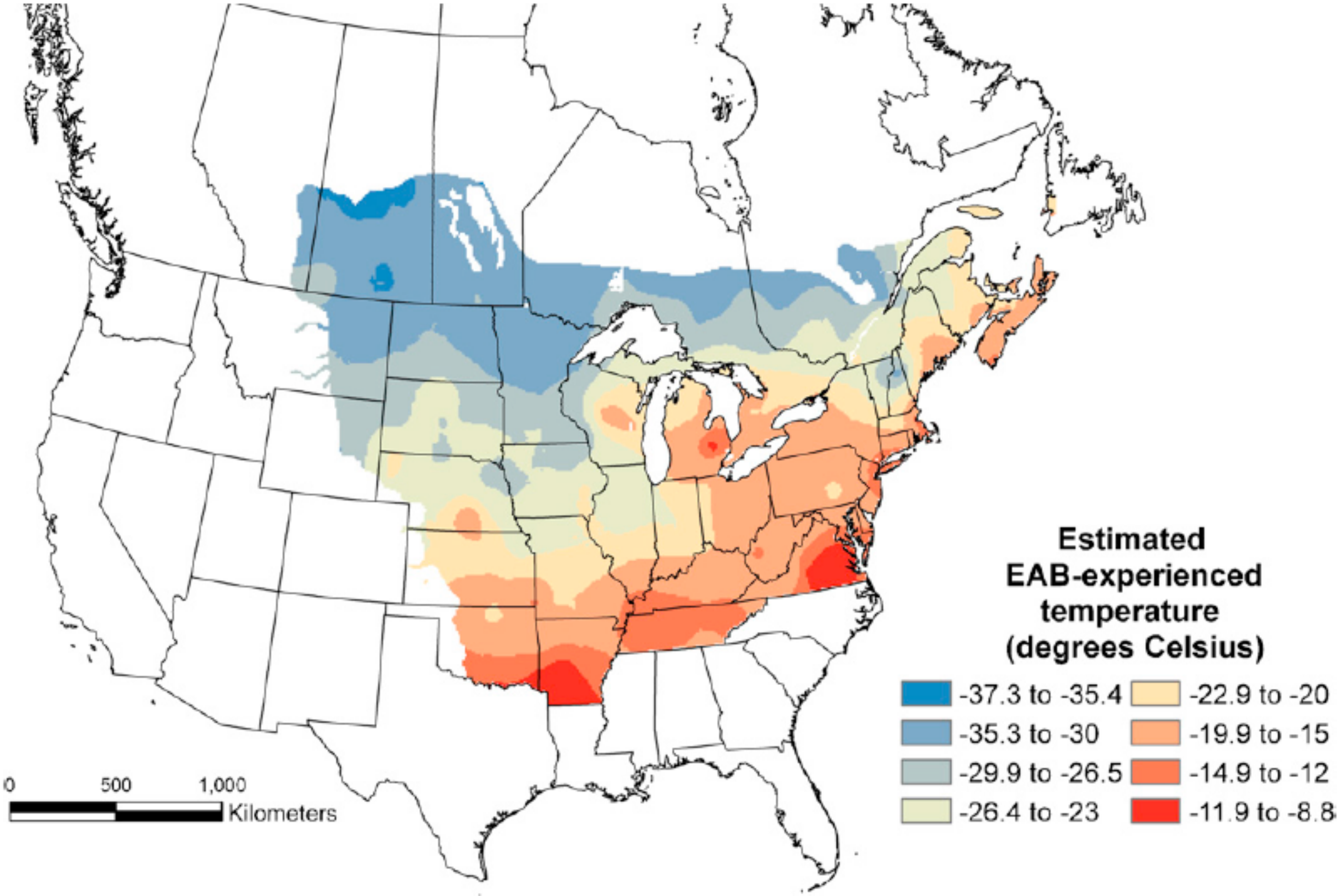


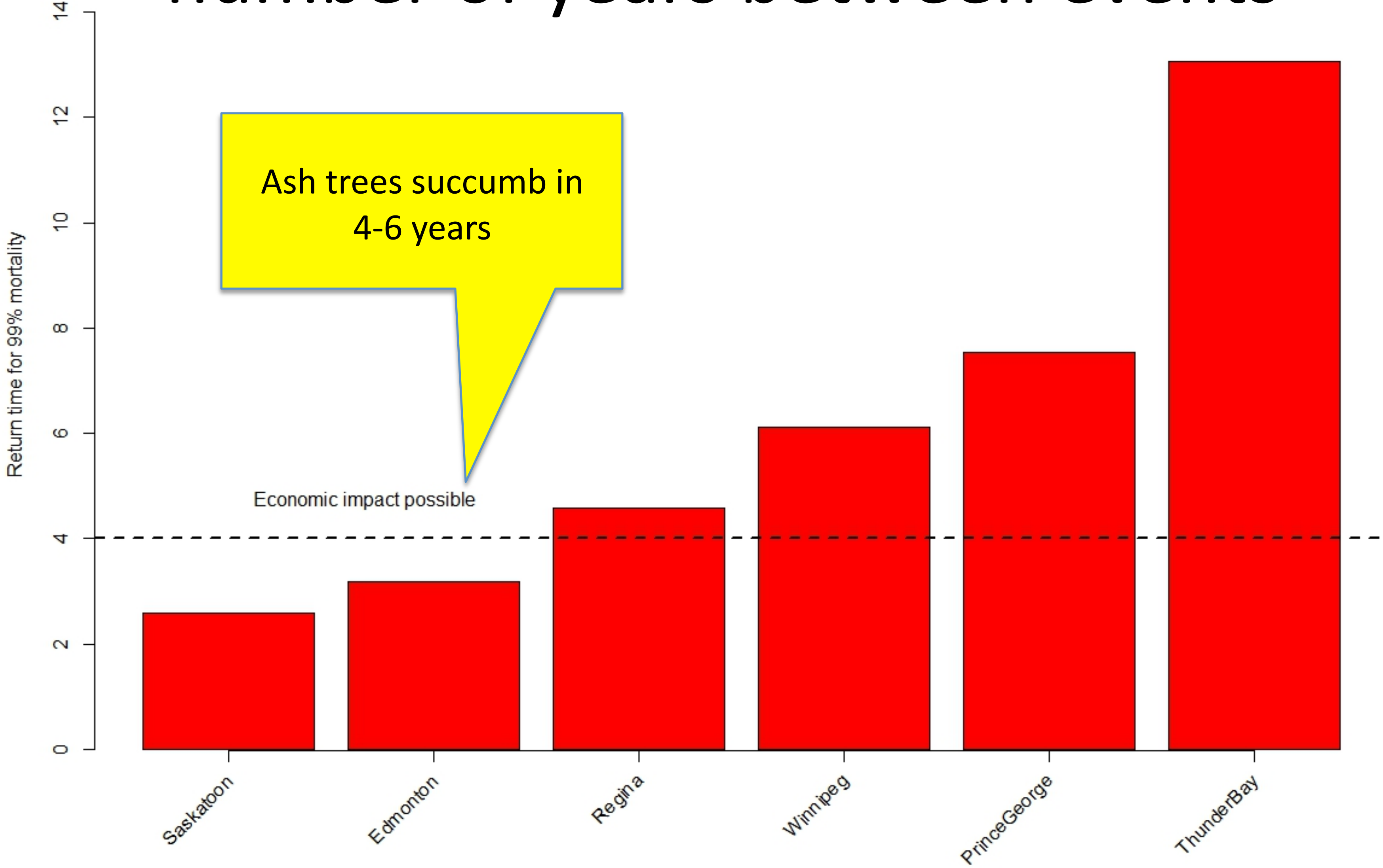
Fig. 2. Coldest estimated EAB-experienced temperatures in the United States and Canada.

DeSantis et al. (2013) Agricultural and Forest Meteorology 178–179: 120–128

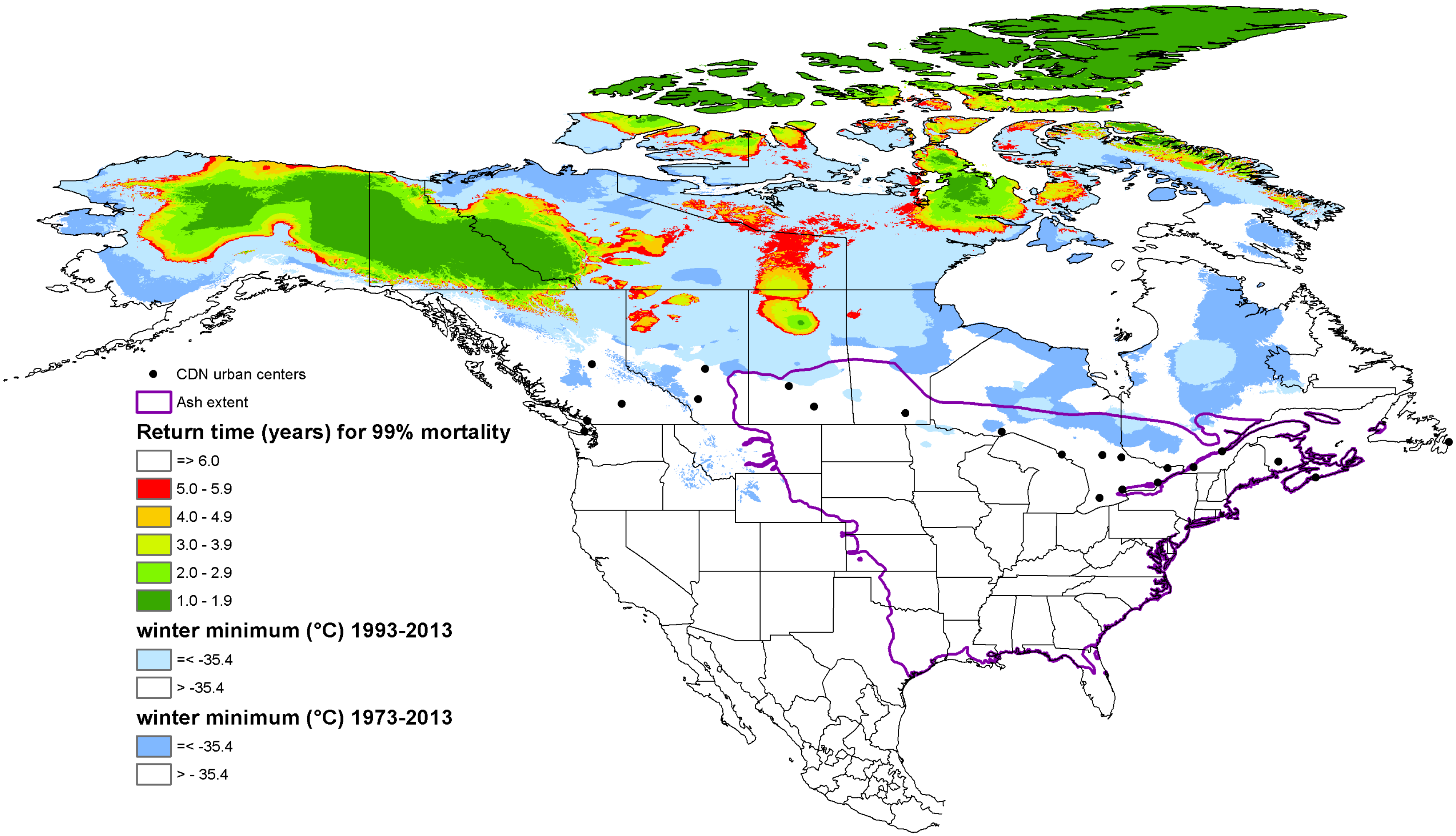
Predict probability of 99% overwintering mortality event

- Collect hourly temp data for 20 years of winters
- Calculate underbark temps using Newtonian cooling model or other best-fit model
- Fit distribution to predicted underbark temps
- Calculate probability of 99% mortality event (-35.5°C)

Return time: Predicted average number of years between events



Return time of 99% mortality events (linear model 1993-2013)



Cuddington et al. (2018) Biol Invasions 20: 2661-2677

Emerald ash borer confirmed in Winnipeg

From: Canadian Food Inspection Agency

News Release

Pest detected outside the regulated area

December 7, 2017 - Ottawa, ON – Canadian Food Inspection Agency

The Canadian Food Inspection Agency (CFIA) has confirmed the presence of emerald ash borer in the city of Winnipeg, Manitoba. The new finding was outside of the regulated area, which includes

Part 1: Conclusions

- **Frequency** of extreme conditions likely important to determine risk of EAB impact (probability of transient persistence)
- Canadian urban centers are toast

2. Initial conditions: Will Asian carp reach large population size in the Great Lakes?

Cuddington et al. (2015). Theoretical Ecology 8: 333-347

Cuddington et al. (2014). Biological invasions 16*:* 903-917

Asian carp (Bighead and Silver)

Small numbers → invasion unlikely

"Just getting a couple fish past the barrier wouldn't be enough to probably start a population. If you have a male and female at the same place at same time it's possible, but the chance of that is not very likely."

Duane Chapman (USGS),

Detroit News Dec 2, 2009

"Lately I've been feeling so alone."

ECOLOGY LETTERS

Ecology Letters, (2011) **14**: 615–624 doi: 10.1111/j.1461-0248.2011.01614.x

REVIEW AND SYNTHESIS

Exploiting Allee effects for managing biological invasions

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**Correspondence: E-mail: ptobin@fs.fed.us*

Abstract

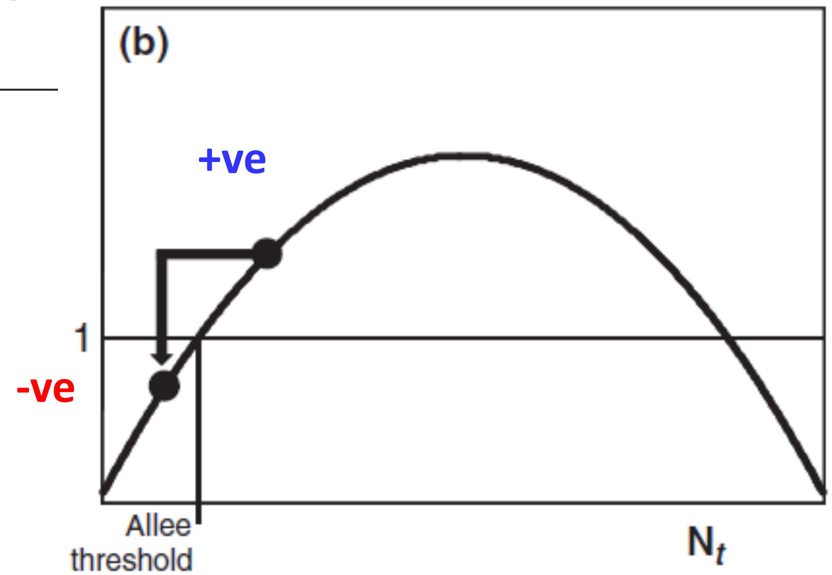
Biological invasions are a global and increasing threat to the function and diversity of ecosystems. Allee effects (positive density dependence) have been shown to play an important role in the establishment and spread of non-native species. Although Allee effects can be considered a bane in conservation efforts, they can be a benefit in attempts to manage non-native species. Many biological invaders are subject to some form of an Allee effect, whether due to a need to locate mates, cooperatively feed or reproduce or avoid becoming a meal, yet attempts to highlight the specific exploitation of Allee effects in biological invasions are surprisingly unprecedented. In this review, we highlight current strategies that effectively exploit an Allee effect, and propose novel means by which Allee effects can be manipulated to the detriment of biological invaders. We also illustrate how the concept of Allee effects can be integral in risk assessments and in the prioritization of resources allocated to manage non-native species, as some species beset by strong Allee effects could be less successful as invaders. We describe how tactics that strengthen an existing Allee effect or create new ones could be used to manage biological invasions more effectively.

Keywords

Allee dynamics, biological invasions, component Allee effect, demographic invasive species management, non-native species.

Ecology Letters (2011) **14**: 615–624

Allee effect:
Population growth rate becomes negative
if population size is too small



“Landmarking”

Journal of Research on the Lepidoptera 7(4):191-204, 1968(1970)

1160 W. Orange Grove Ave., Arcadia, California, U.S.A. 91006

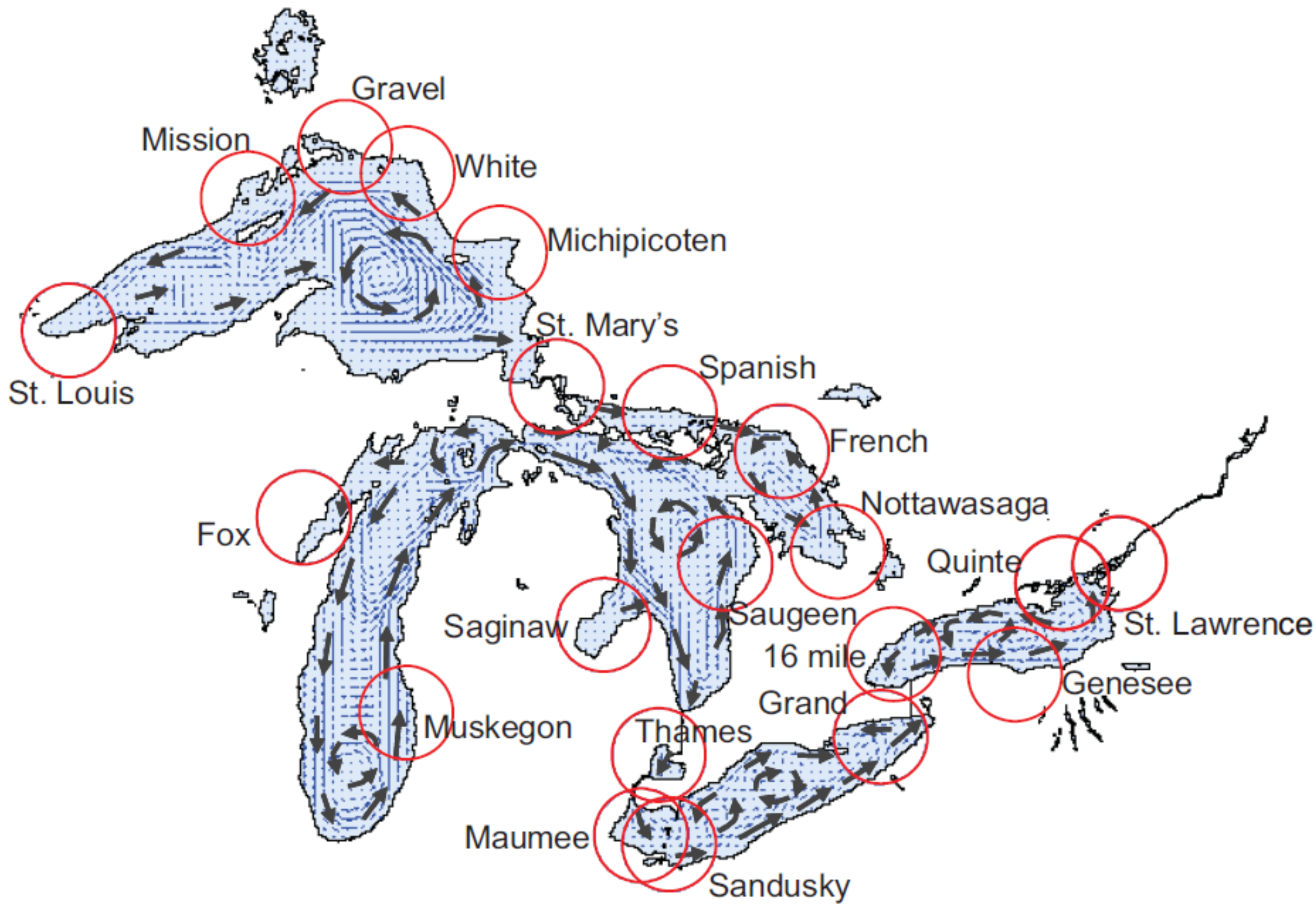
HILLTOPPING AS A MATING MECHANISM TO AID THE SURVIVAL OF LOW DENSITY SPECIES

JAMES A. SCOTT
201 Wellman Hall
Univ. of California
Berkeley, California 94720

“Landmark mating strategies involve species setting up mating aggregations over any conspicuous marker. This can range from a rock to a tuft of grass, a road, a stream course, a bog an emergent tree (taller than the others), or a hilltop.”

Jeffrey Skevington AgCanada

Potentially suitable rivers for Asian Carp spawning



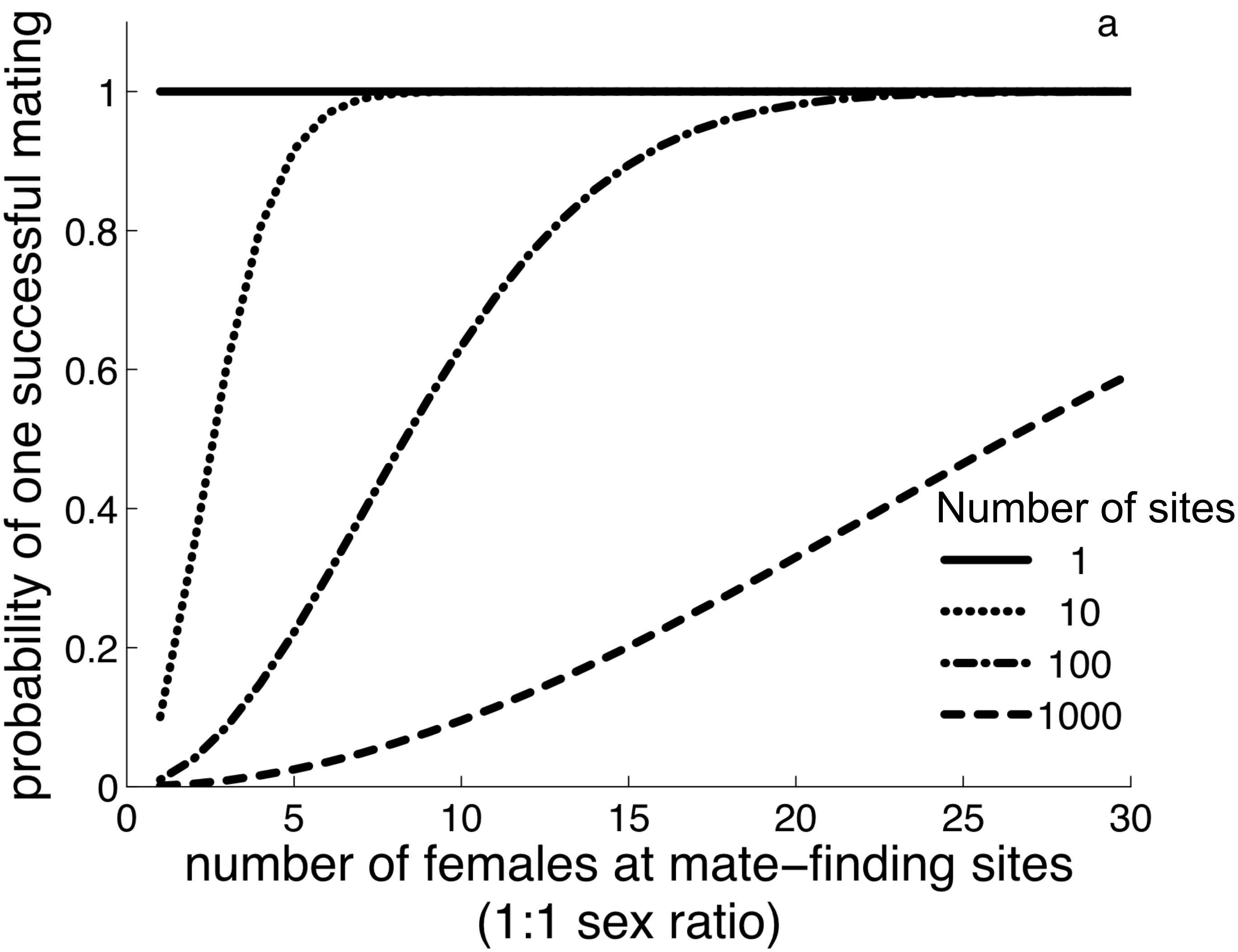
Side note: Probability of no successful matings

$$P_0(m,f,r) = \frac{1}{r^{m+f}} \sum_{i=1}^{m} \sum_{j=1}^{f} S_2(m,i) S_2(f,j) \prod_{k=0}^{i+j+1} r-k$$

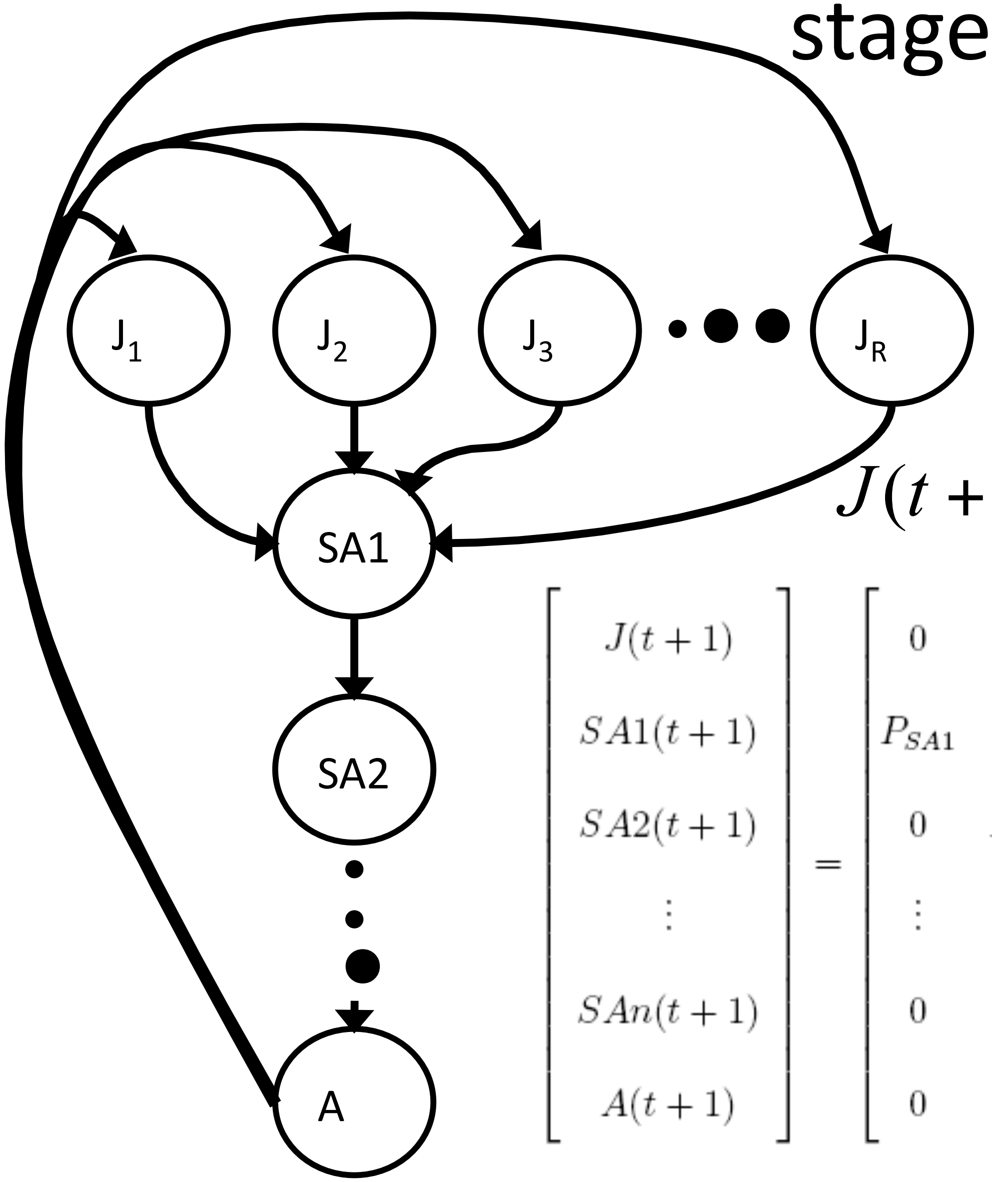
where $m = males, f = females$ and $r = sites$

following Wendl (2003)

Mating probability is inversely related to the number of mate-finding sites



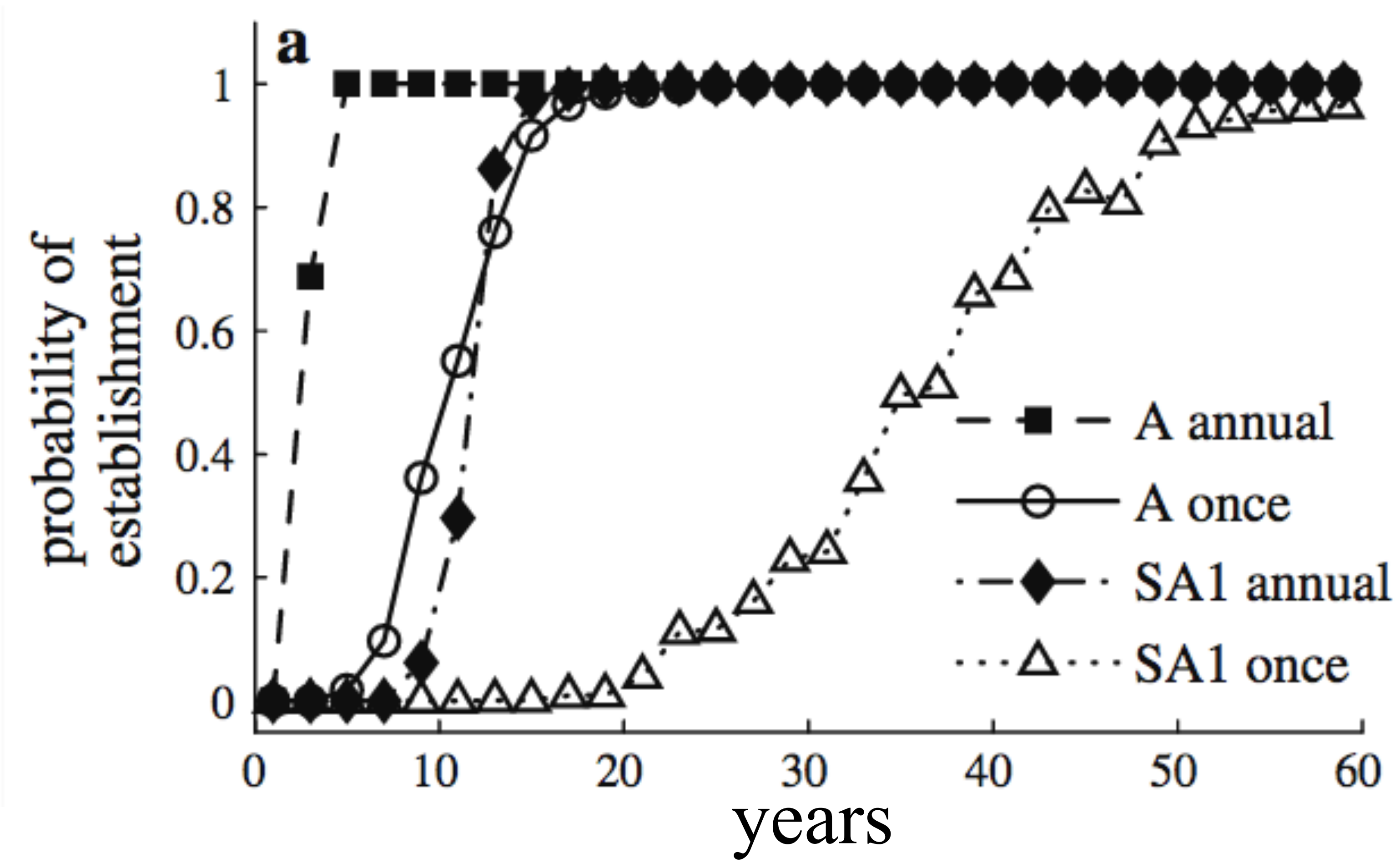
Spawning river (R) subdivided stage-structured model



$$J(t+1) = \sum_{i=1}^{r} J_i(t+1) = \sum_{i=1}^{r} \left(M_i P_J F_i \right)$$

$$\begin{bmatrix} J(t+1) \\ SA1(t+1) \\ SA2(t+1) \\ \vdots \\ SAn(t+1) \\ A(t+1) \end{bmatrix} = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 & F/2 * P_J \\ P_{SA1} & 0 & \dots & 0 & 0 & 0 \\ 0 & P_{SA2} & \dots & 0 & 0 & 0 \\ \vdots & \vdots & \dots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & P_{SAn} & 0 & 0 \\ 0 & 0 & \dots & 0 & P_A & P_A \end{bmatrix} \times \begin{bmatrix} J(t) \\ SA1(t) \\ SA2(t) \\ \vdots \\ SAn(t) \\ A(t) \end{bmatrix},$$

Effect of initial conditions for 10 spawning rivers and 10 fish (prob of 1000 fish)



Part 2. Conclusions

- “Landmarking” can be very efficient.
- The effective Allee threshold for species with restricted mating sites can be quite small
- The Chicago Ship and Sanitary Canal is probably not going to prevent Asian carp from establishing a growing population

This June 22, 2017, file photo provided by the Illinois Department of Natural Resources shows a silver carp, a variety of Asian carp, that was caught in the Illinois Waterway below T.J. O'Brien Lock and Dam, approximately nine miles away from Lake Michigan. The U.S. Army Corps of Engineers has released a final $778 million plan to keep Asian carp from reaching the Great Lakes by strengthening defenses at a lock-and-dam complex in Illinois. The price tag is much higher than the estimated cost of a tentative version of the strategy released in 2017. *Illinois Department of Natural Resources via AP*

Partnership Agreement To Address Asian Carp In The Works For Great Lakes States, Provinces

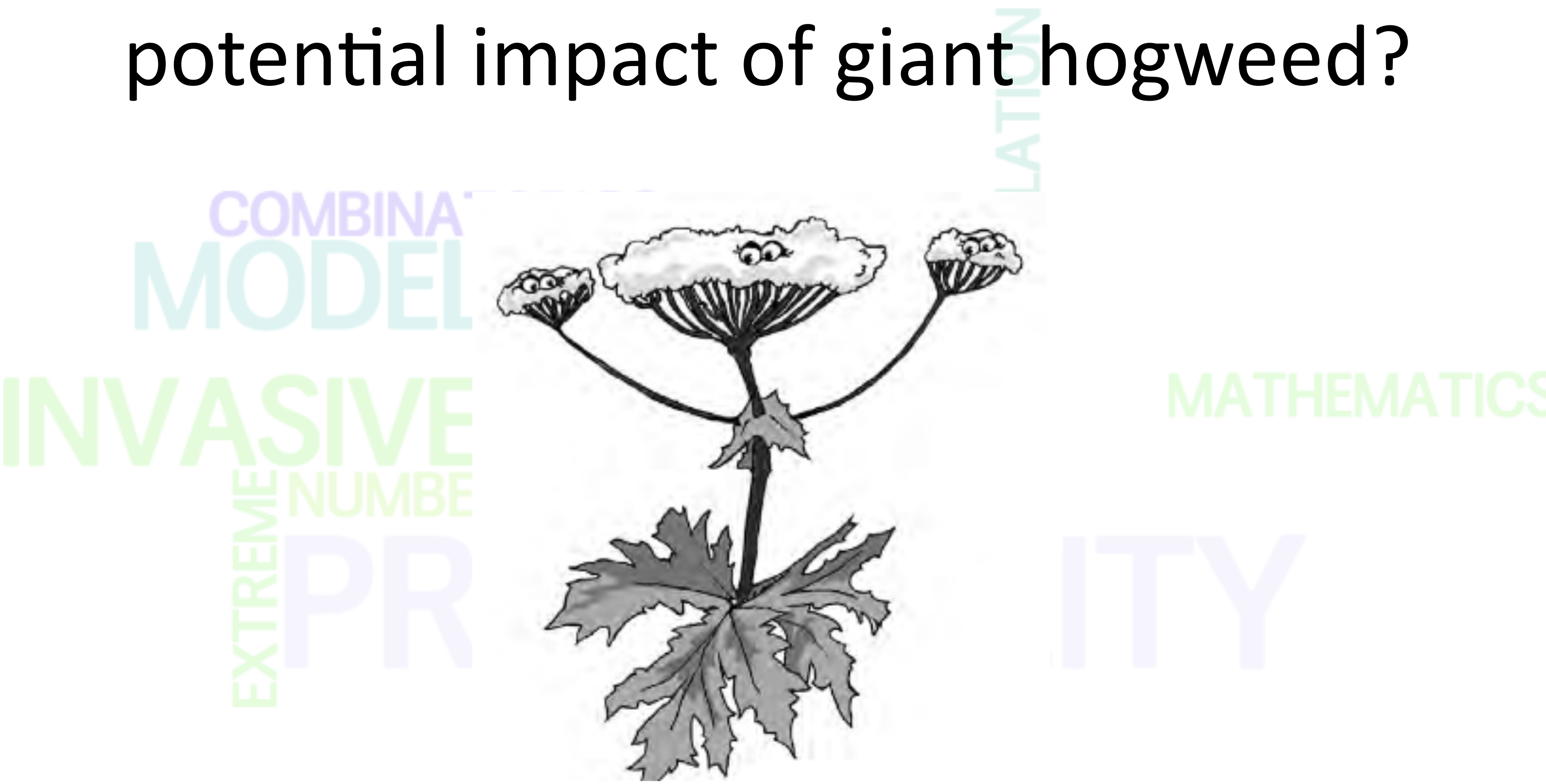
Illinois To Draft Agreement As Part Of Efforts To Move Plan Forward

By Danielle Kaeding

Published: Friday, July 19, 2019, 7:55am

NPR.org

3. Internal dynamics: How do temperature autocorrelation and life history affect the potential impact of giant hogweed?



Drake (2019) MMath Thesis

Cuddington & Hastings (2016) Oikos 125: 1027-1034

Subtopics

1. Autocorrelation and transient population size in a simple model
2. Side note: Effect of temperature autocorrelation on thermal response
3. Effect of integrated temperature on giant hogweed life history

↑Environmental Variance
↓ Population growth

- Expected population growth is given by the geometric mean of a time-varying growth rate (Lewontin & Cohen 1969)

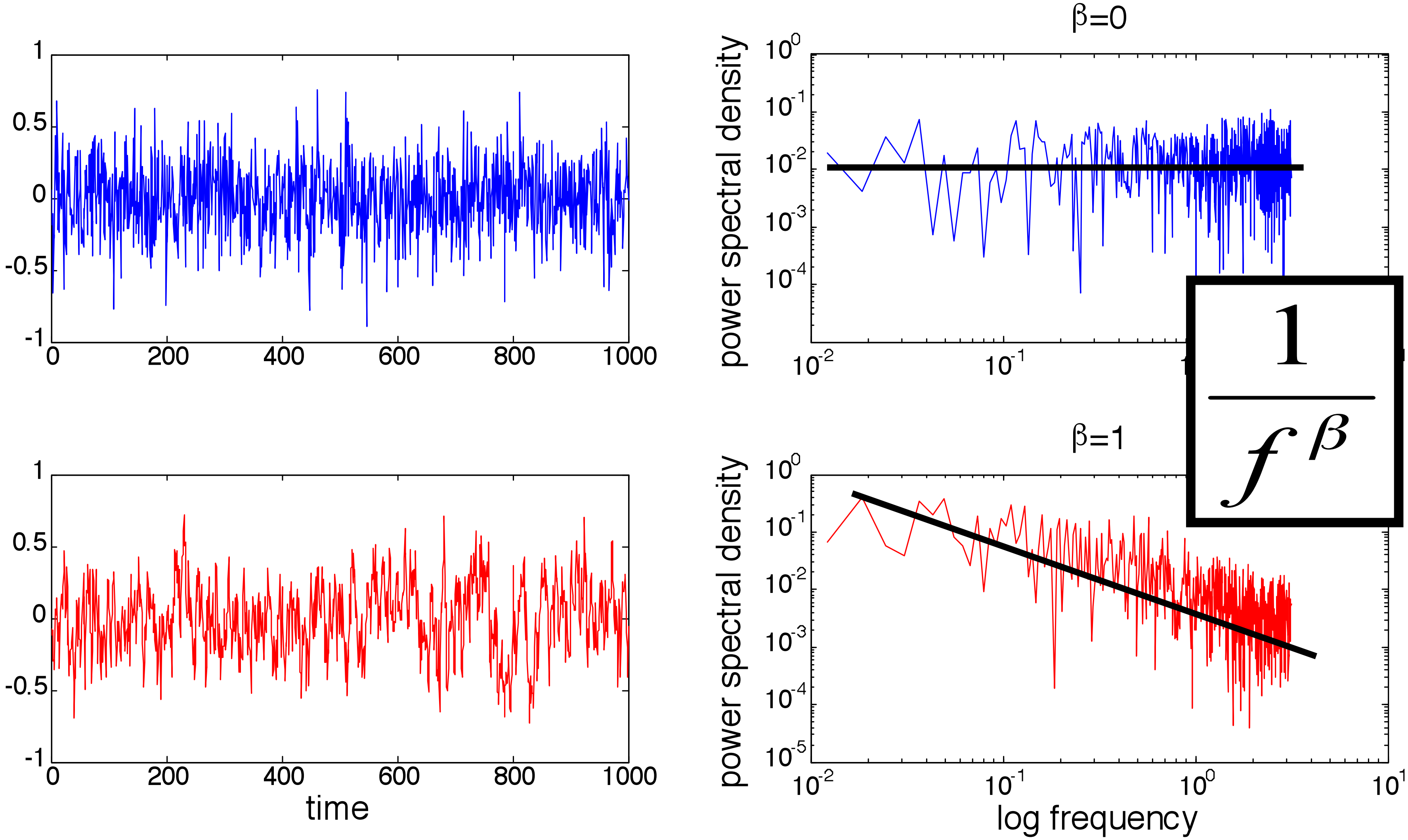
- $N_1=\lambda_0 N_0$, and $N_2=\lambda_1 N_1$ => $N_2= \lambda_1\lambda_0 N_0$,
- and more generally: $N_{t+1} = (\lambda_t\lambda_{t-1}\lambda_{t-2}\ldots\lambda_1\lambda_0)N_0$
- Geometric mean $\bar{\lambda}_G = \left(\prod_t \lambda(t)\right)^{\frac{1}{t}}$
- Geometric mean λ_G decreases with increased variance

Environmental variation is positively autocorrelated (reddened)

Environmental characteristic	**Spectral exponent, β (-slope)**	**Reference**
monthly temperature	0.07-1.19	Cyr & Cyr 2003
earthquake frequency	0.34	Lapenna et al. 1998
mean air temperature	0.43	Pelletier 1997
air humidity	0.61	Vattay & Harnos 1994
SST	1.5	Vasseur & Yodzis 2004
annual river minima	2.82	Mandelbrot & Wallis 1969

Cuddington & Yodzis 1999 Proc. Roy. Soc B 266:969-973

No autocorrelation (blue) vs. strong positive autocorrelation (red)



3.1 Geometric population growth with autocorrelated noise

- Using a simple geometric growth model with variable and autocorrelated growth rate

$$N_{t+1} = N_t \lambda_t \quad \text{or} \quad N_{t+1} = N_t \exp(r_t)$$

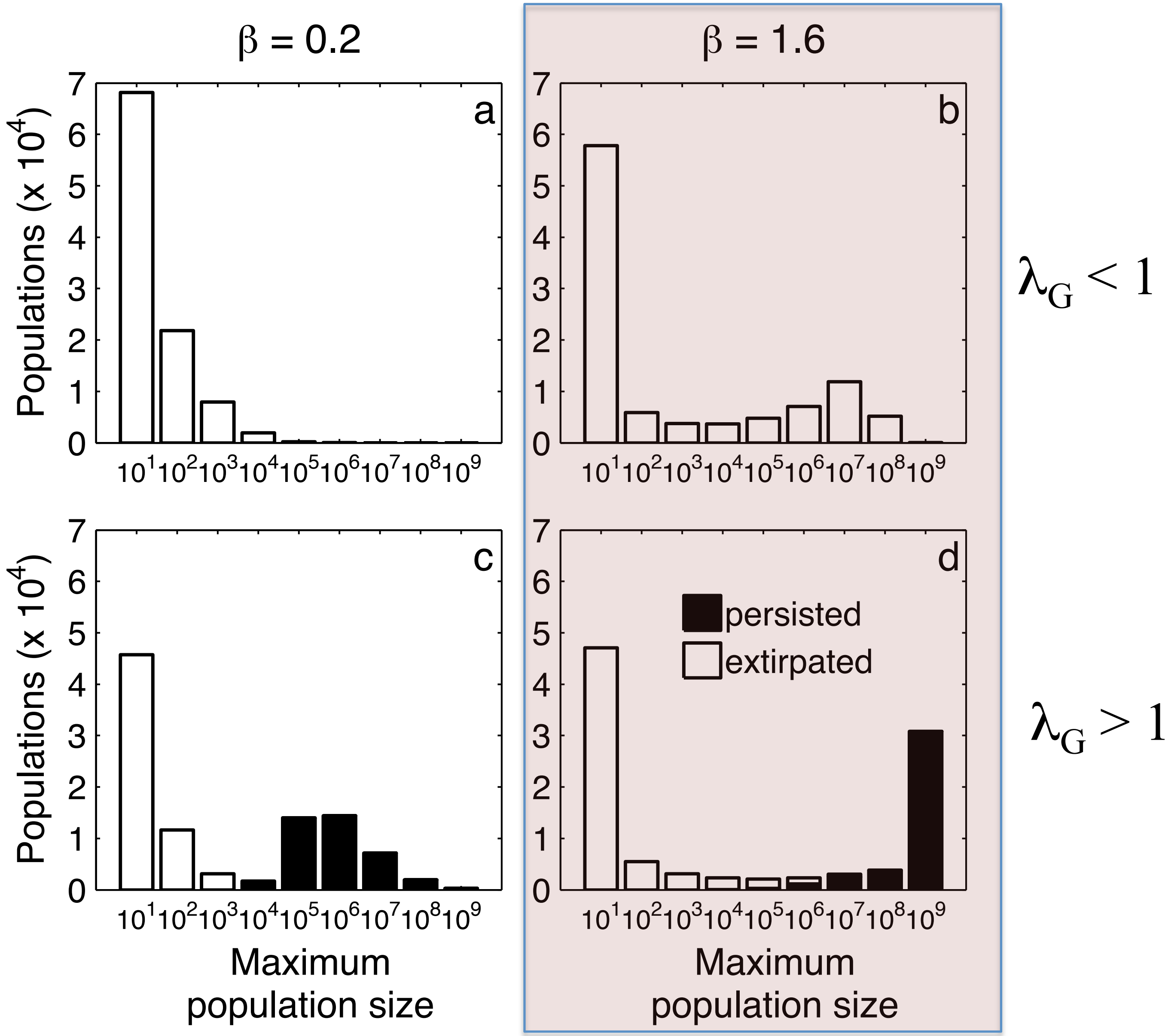
where $r_t = r_0 + \varepsilon_t$, and ε_t is drawn

from a positively autocorrelated process ($1/\mathrm{f}^{\beta}$)

Larger β =
larger autocorrelation

- Simulate population growth times (100,000 reps)
- Determine probabilty of persistence and probability of reaching large population size

Large autocorrelation can lead to large population size without persistence



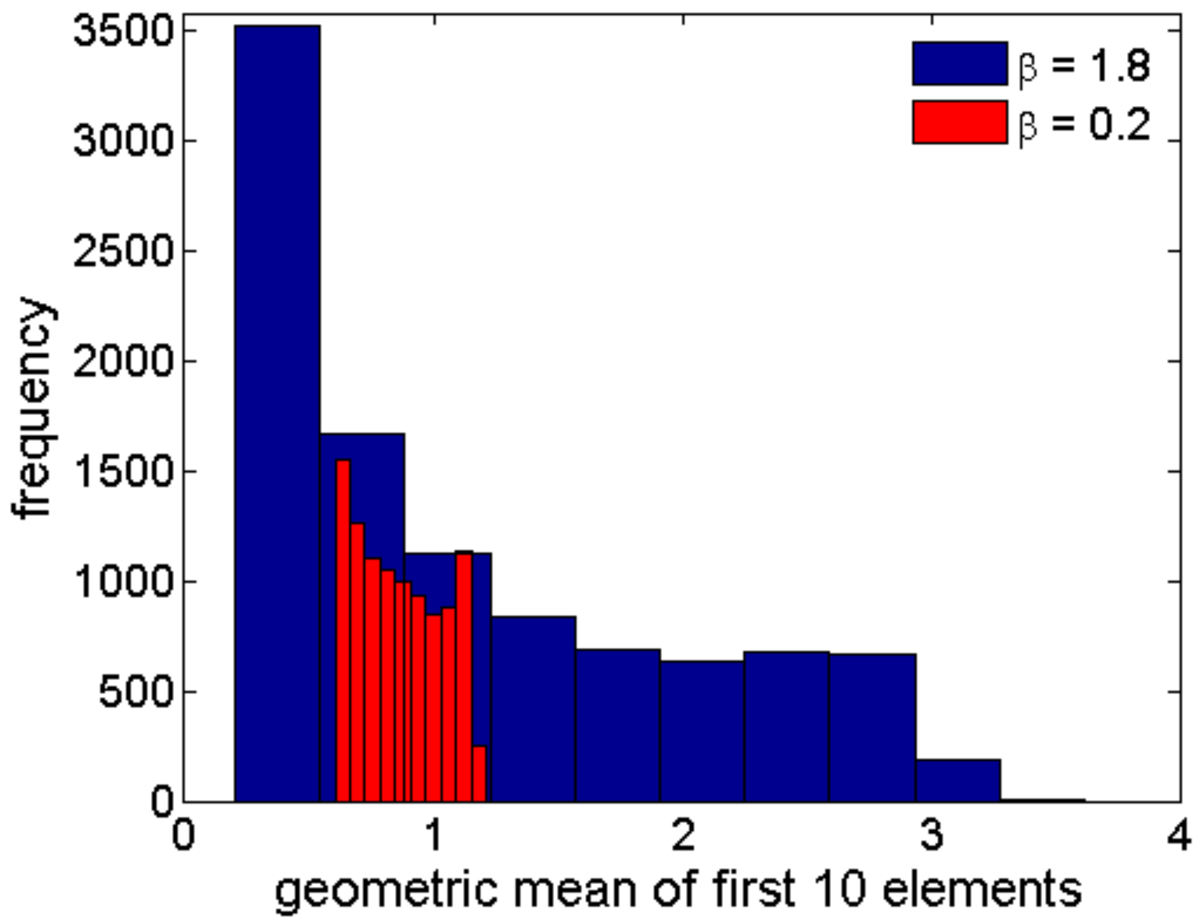
Cuddington & Hastings 2016 Oikos 125: 1027-1034.

Explanation?

Probability of passing a threshold poulation size:

1. the overall expected population growth rate ($\uparrow\lambda_G$) and
2. the variance of the signal ($\downarrow\sigma$)
3. the initial environmental conditions (for example $\lambda_{1\ldots10}$), which are determined by autocorrelation

Explanation: Autocorrelation (and sufficient variance) can increase the probability of highly beneficial initial environmental conditions



Part 3.1: Conclusions

- Early beneficial conditions increase probability of large population size even in non-persistent populations
- Autocorrelation of environmental signals can increase the invasive impact for “low risk” populations

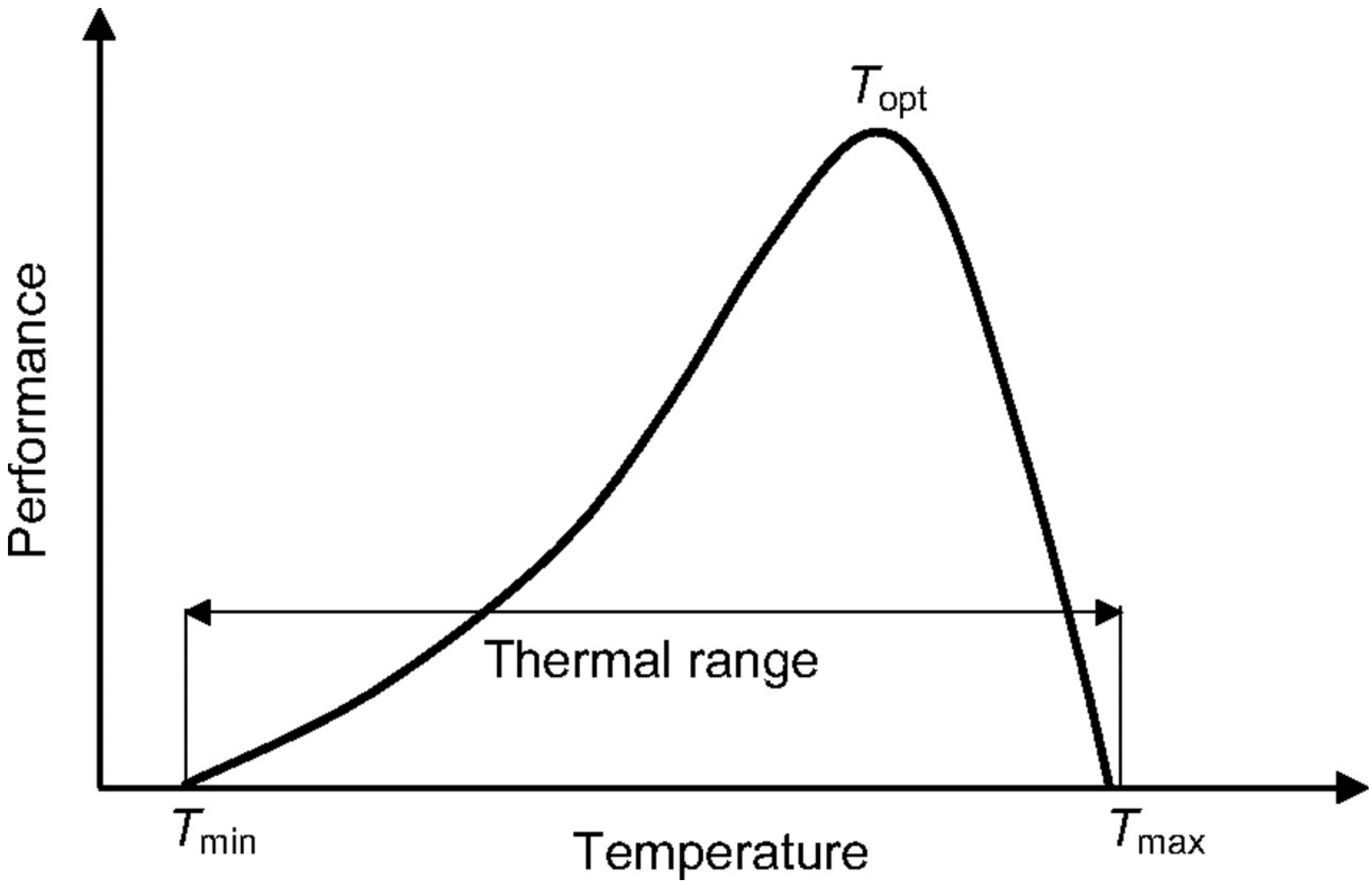
- However, this is a ridiculously simple population model, what about life history??

3.2 Autocorrelated temperature deviations and life history

- All air temperature data is positively autocorrelated
- Autocorrelation determines probability of extreme events such as cold snaps and heat waves
- Does autocorrelation affect life history?
  - e.g., One year to maturity? Two? Overwintering survivial rates? Etc?

Thermal performance curves

The thermal performance reaction norm, which relates some parameter representative of organismal performance (e.g. running speed, feeding rate, growth, reproductive output) to body temperature [adapted from Angilletta, (2009)].



Ratkowsky equation

$$rate = \left(c\left(T - T_L\right)\right) * \left(1 - \exp\left(k\left(T - T_U\right)\right)\right)^2$$

where T is the current temperature,

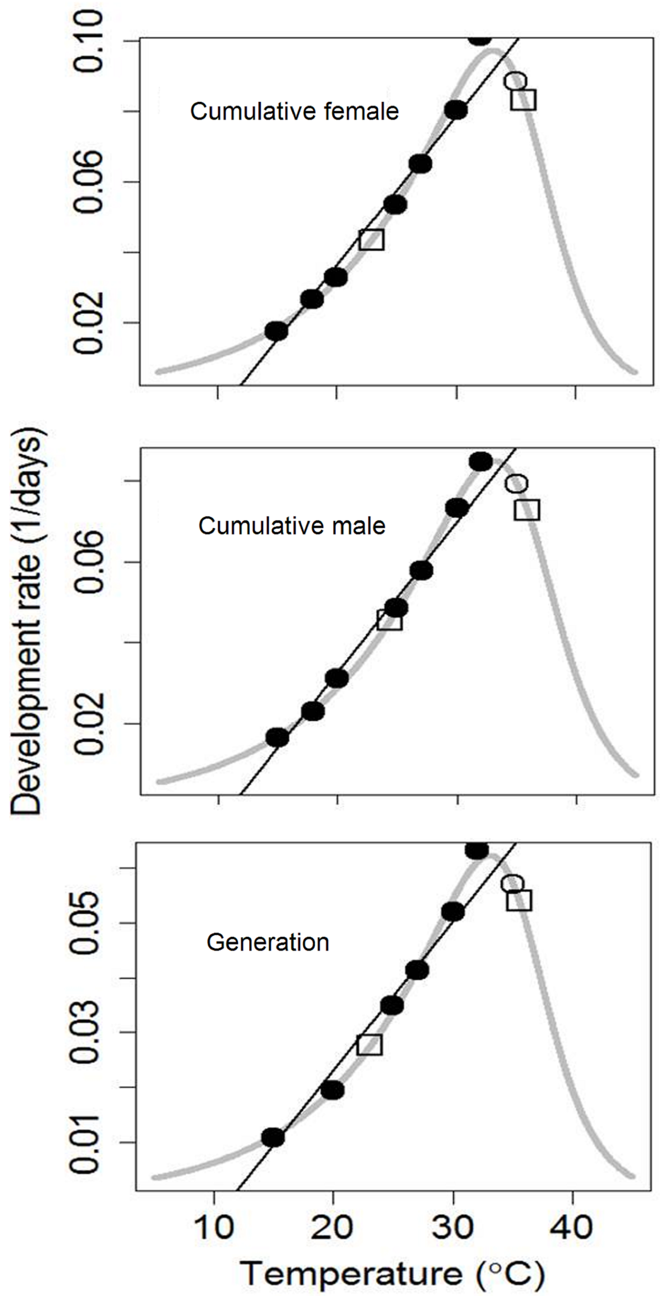
T_L is the lower temperature threshold,

T_U is the upper temperature threshold

c rate parameter for response to cold temps

k shape/rate parameter for response to hot temps

Quinn 2017; Roitberg & Mangel 2016

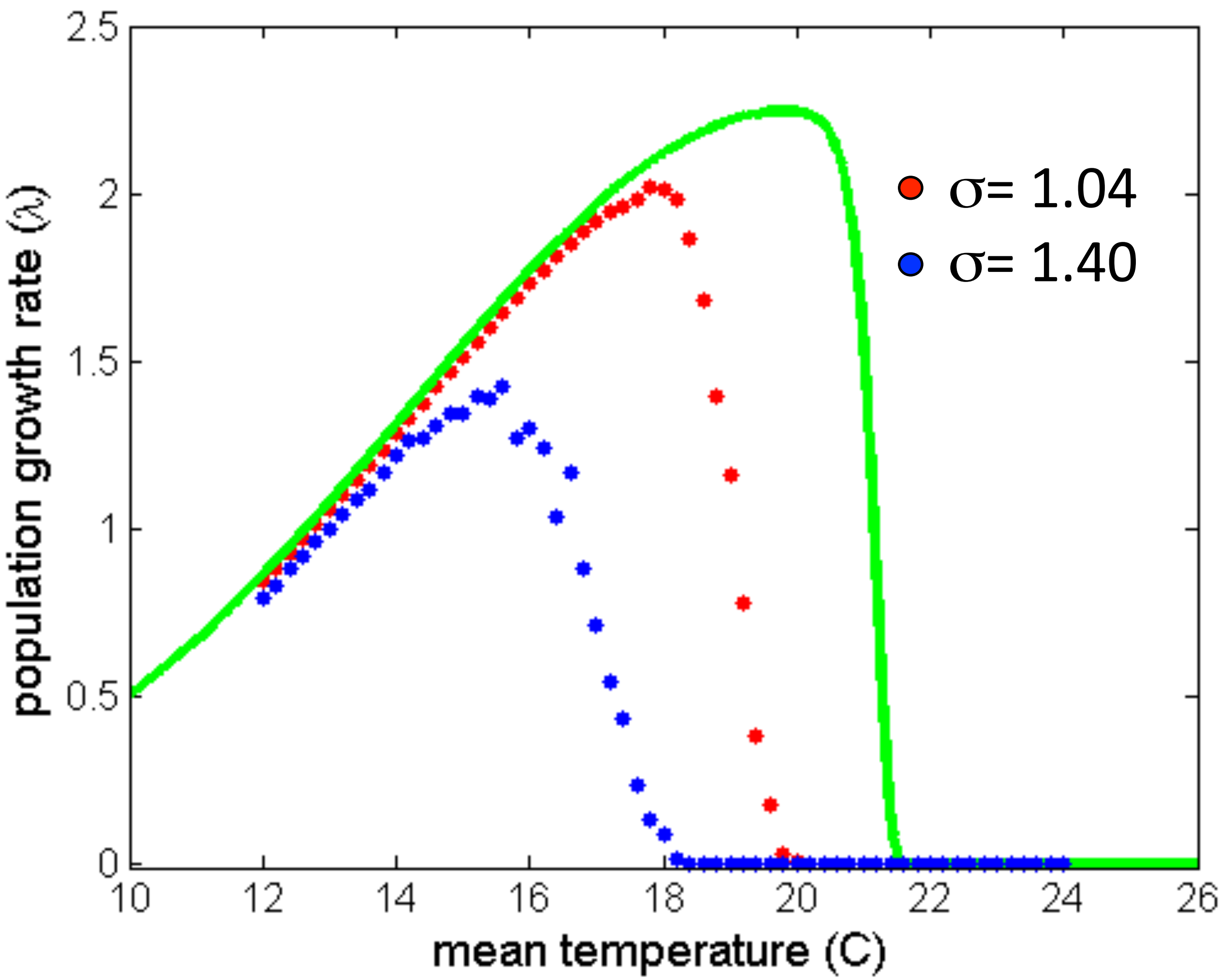


Side Note: Thermal performance curves and degree-days

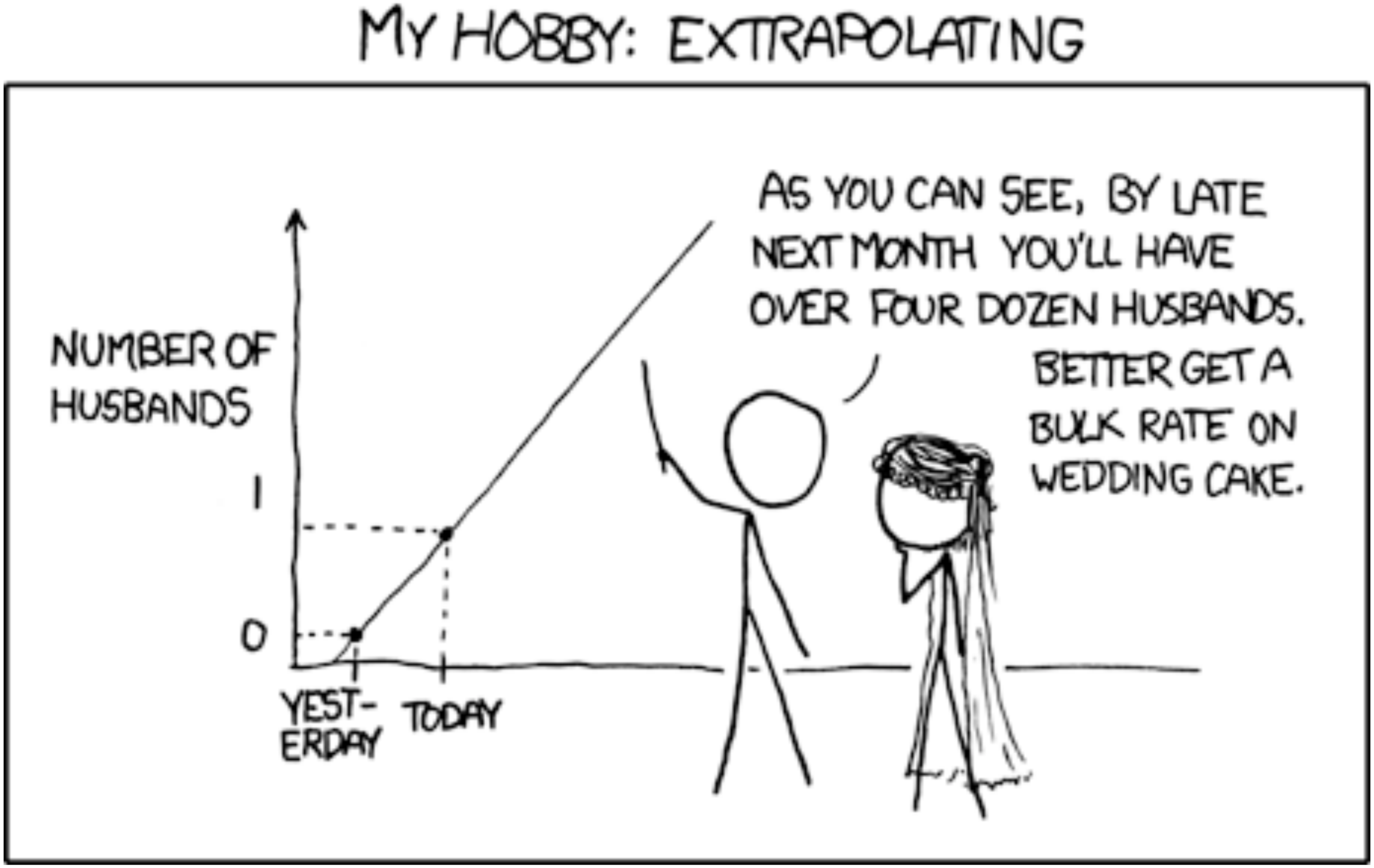
- mean developmental rate and generation time of the mealybug *Phenacoccus solenopsis*

Sreedevi et al. (2013)

Suboptimal: Its the new optimal

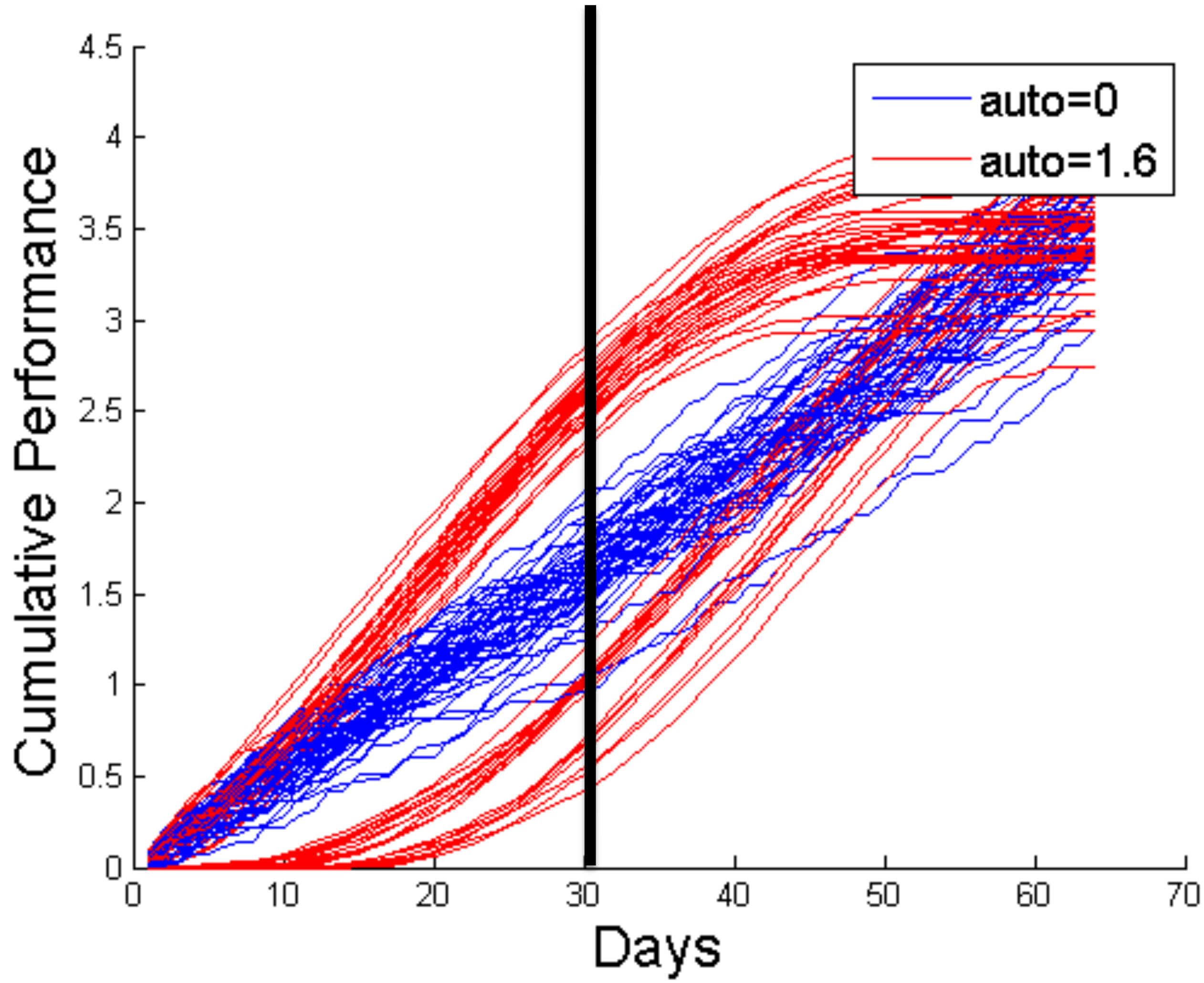


Jensen's inequality, but also see Martin and Huey 2008)

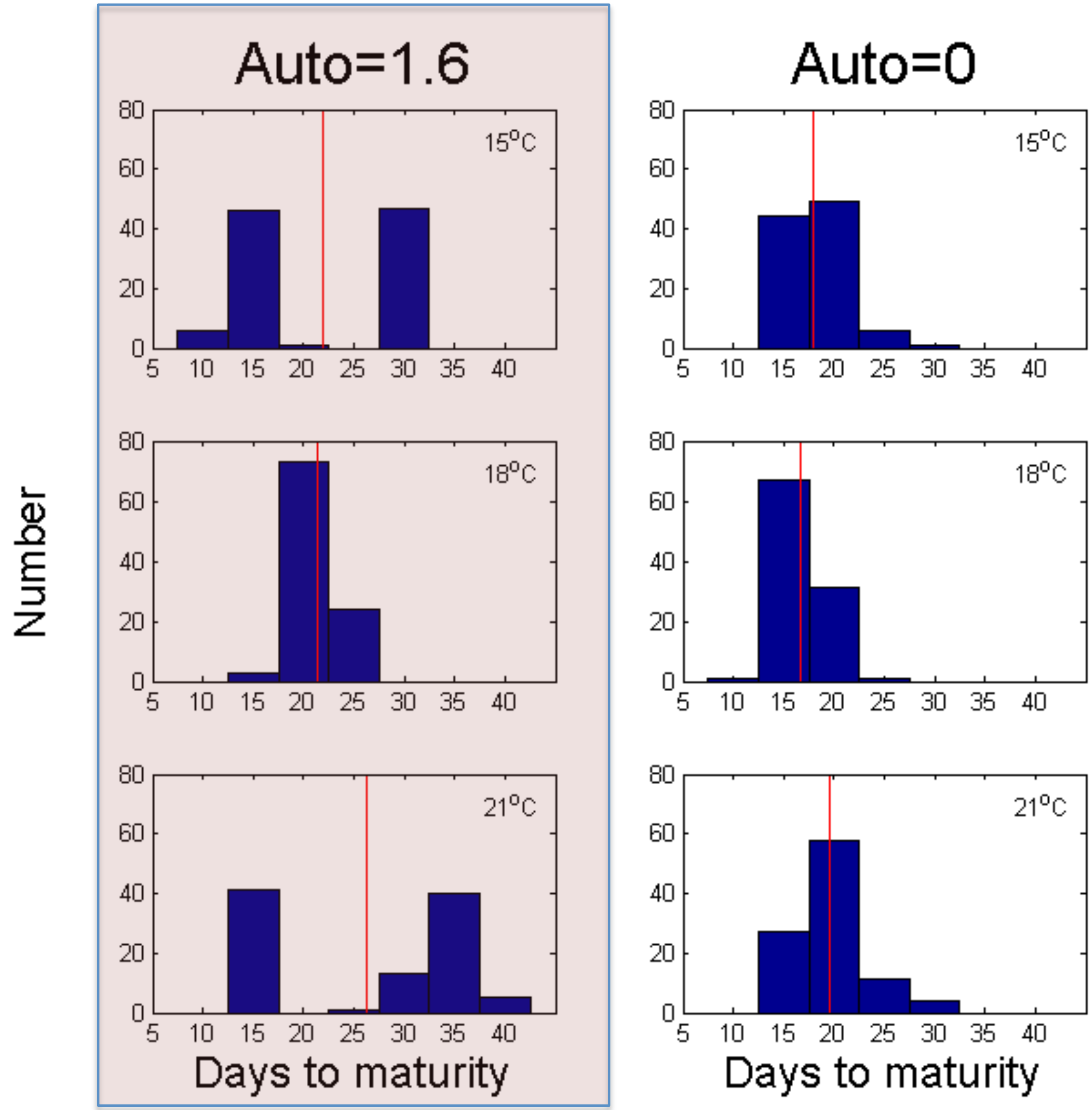


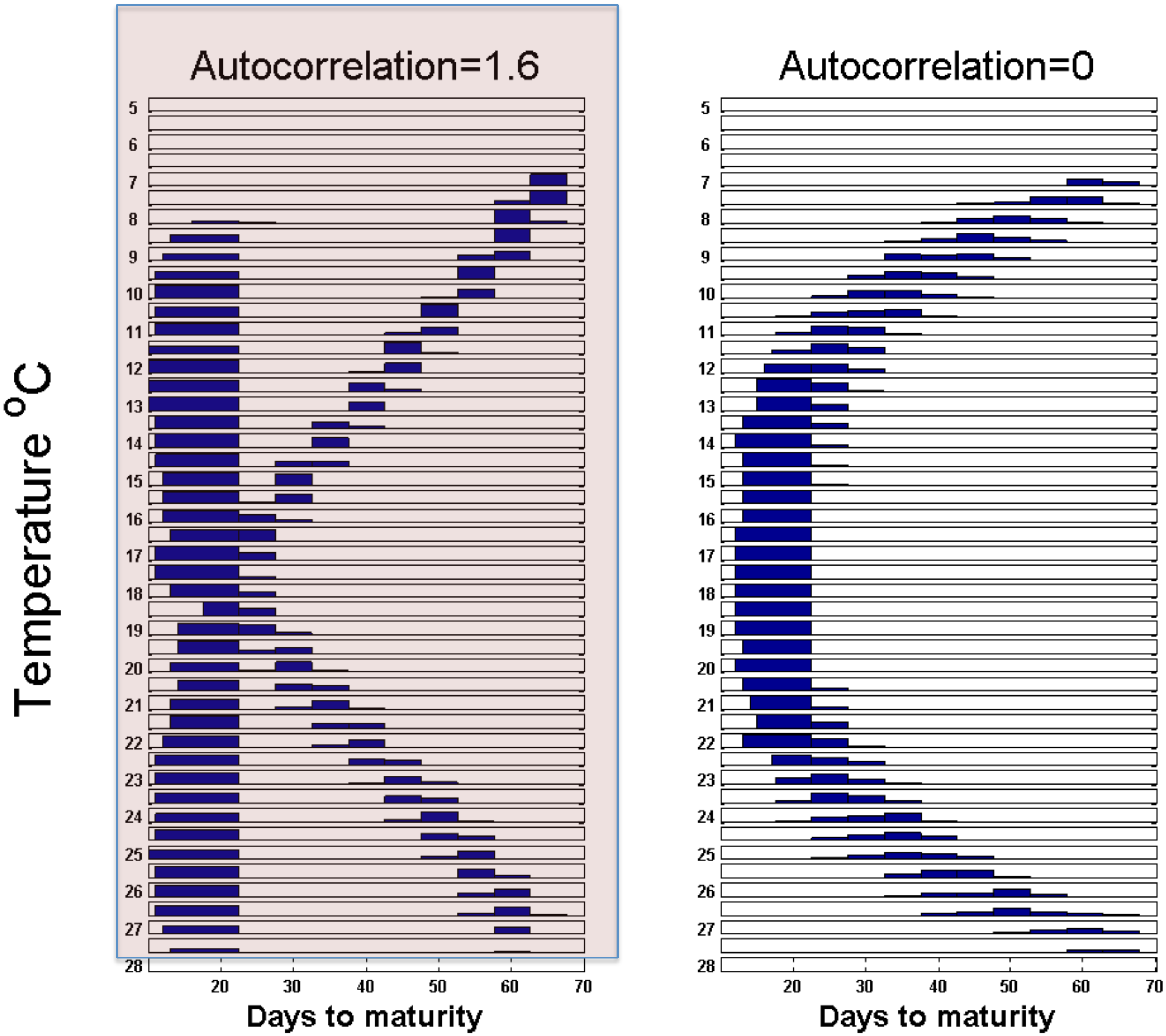
https://xkcd.com/605/

Autocorrelation affects trajectories



Therefore autocorrelation alters probability of life history events in a given time




Autocorrelation=1.6
Autocorrelation=0
Temperature °C
Days to maturity
Days to maturity
5
6
7
8
9
10
11
12
13
14
15
16
17
18
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60
70

Part 3.2: Conclusions

1 If mean temperature isn't near the optimum of a TPC you cannot ignore autocorrelation
2 If autocorrelation is important, the mean thermal performance is probably not

For example, fast development times may be probable in temp regimes where the mean predicts slow development

3.3 Case Study: Integrated thermal impacts, life history of giant hogweed, and transient behaviour

CANADA July 15, 2019 3:50 pm

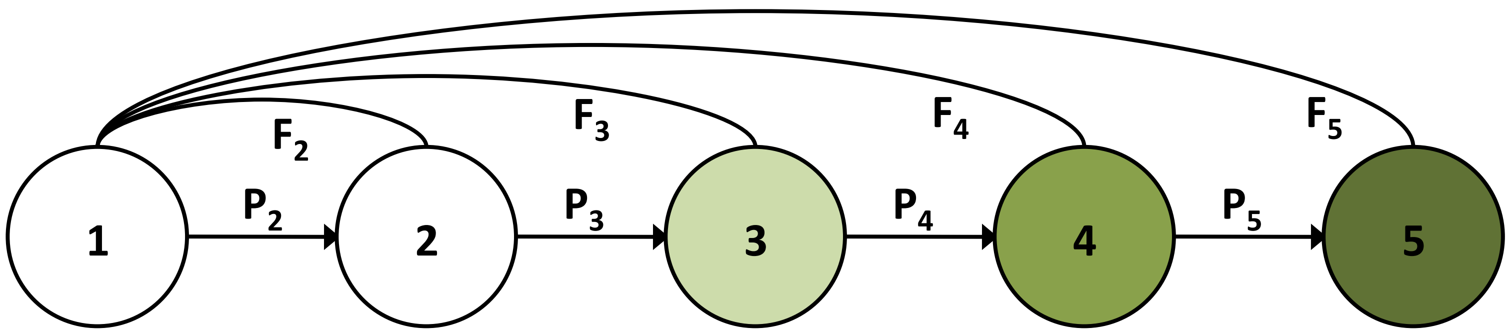
City of Waterloo issues warning over hogweed plants

By Kevin Nielsen Local Online Journalist Global News

Giant hogweed produces a toxin capable of causing a severe skin rash.

Leslie J. Mehrhoff, University of Connecticut / Global News

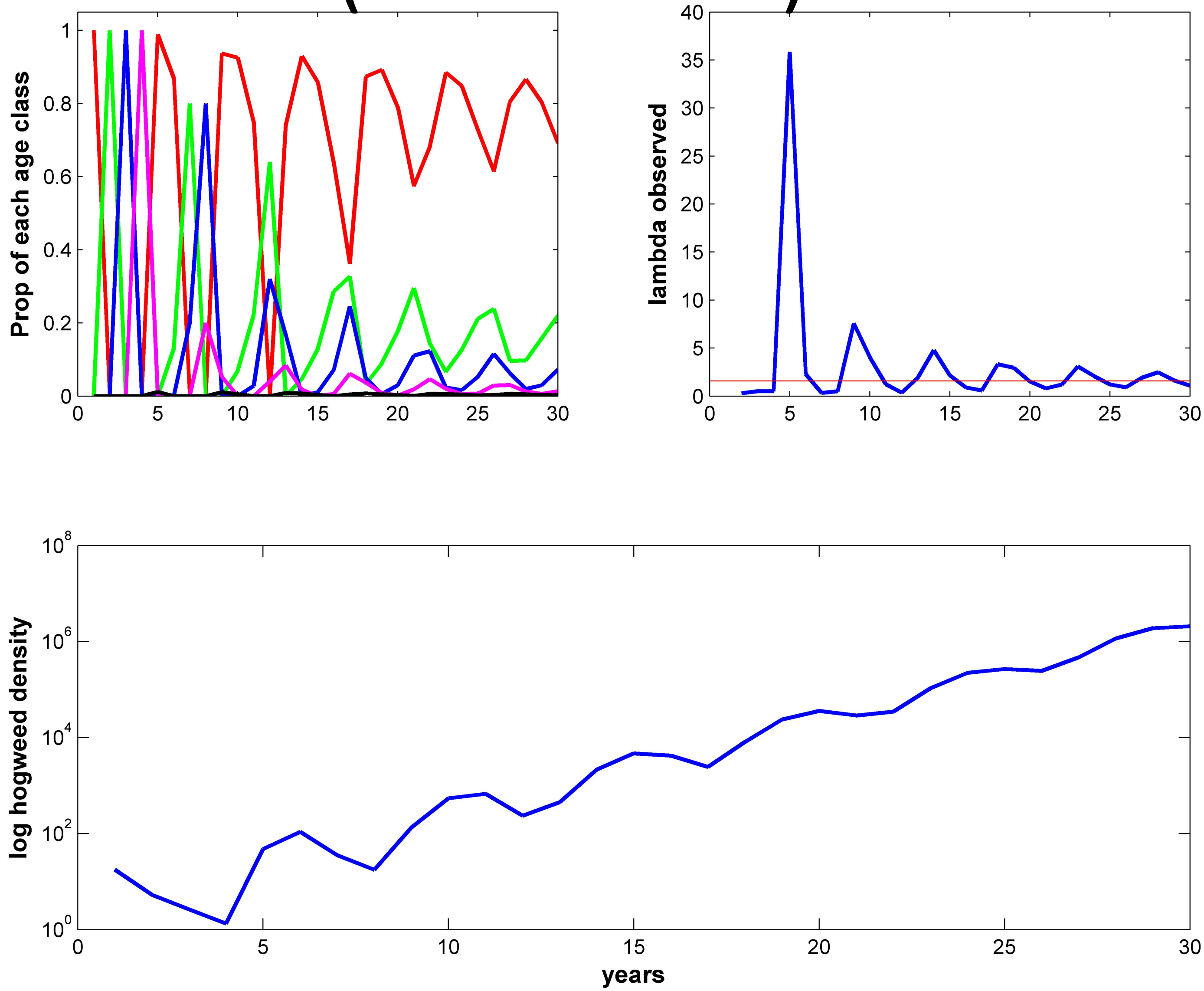
Age-structured population model of giant hogweed



$P_{2\text{-}5}$ = 1 – prob. flowering at age x – prob. death before flowering at age x

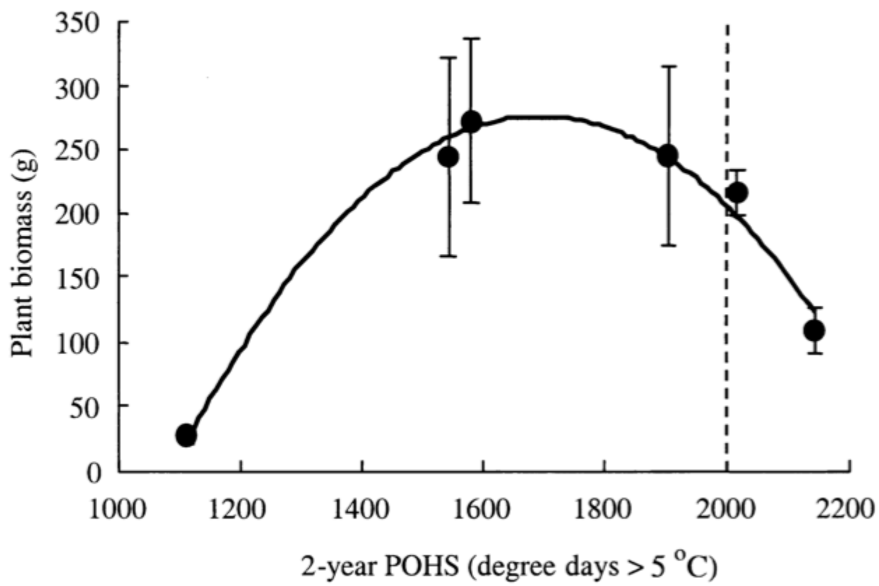
F_x = (# viable seeds per plant)*(prob. flowering at age x)*(prob. of surviving to age 1)

Transients in hogweed model (1000 seeds)

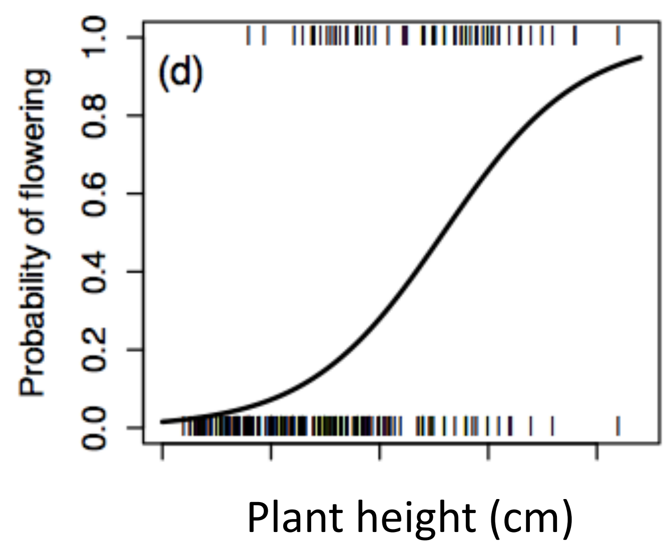


Temperature and giant hogweed life history

Biomass accumulation vs degree days



Probability of flowering vs biomass

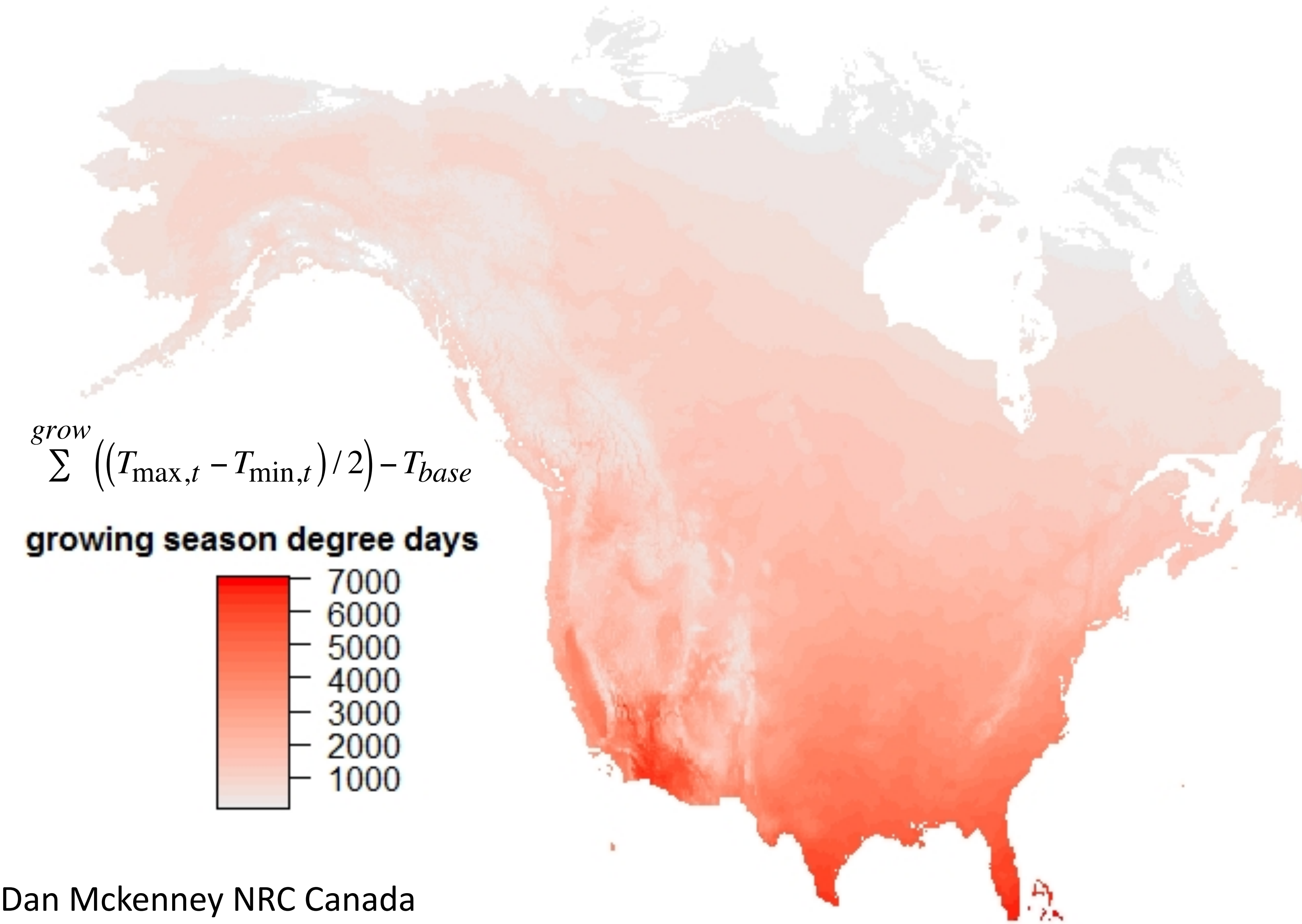


Willis et al. 2002

Drake 2019

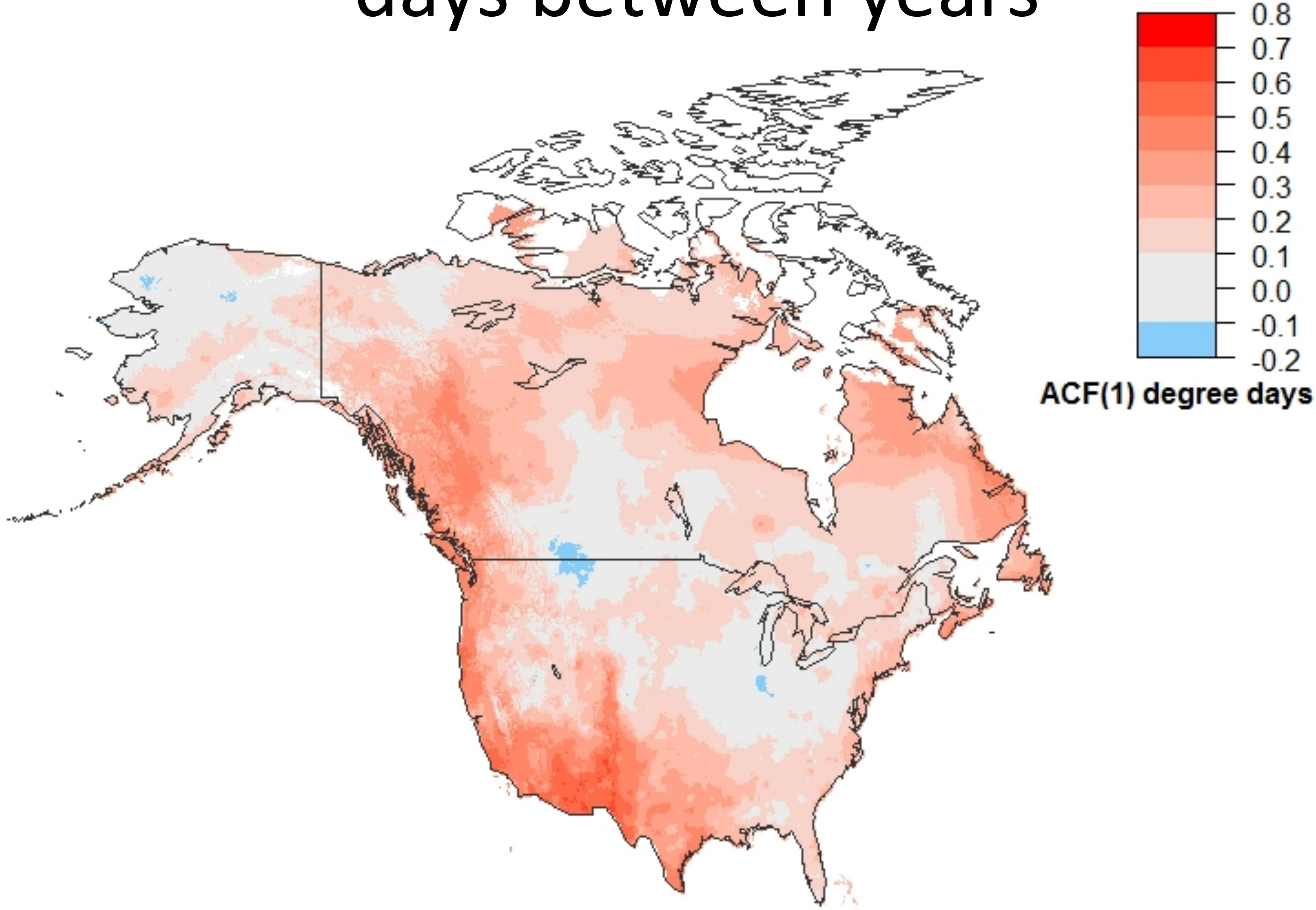
Mean growing degree days

$$\sum^{grow}\left(\left(T_{\max,t} - T_{\min,t}\right)/2\right) - T_{base}$$

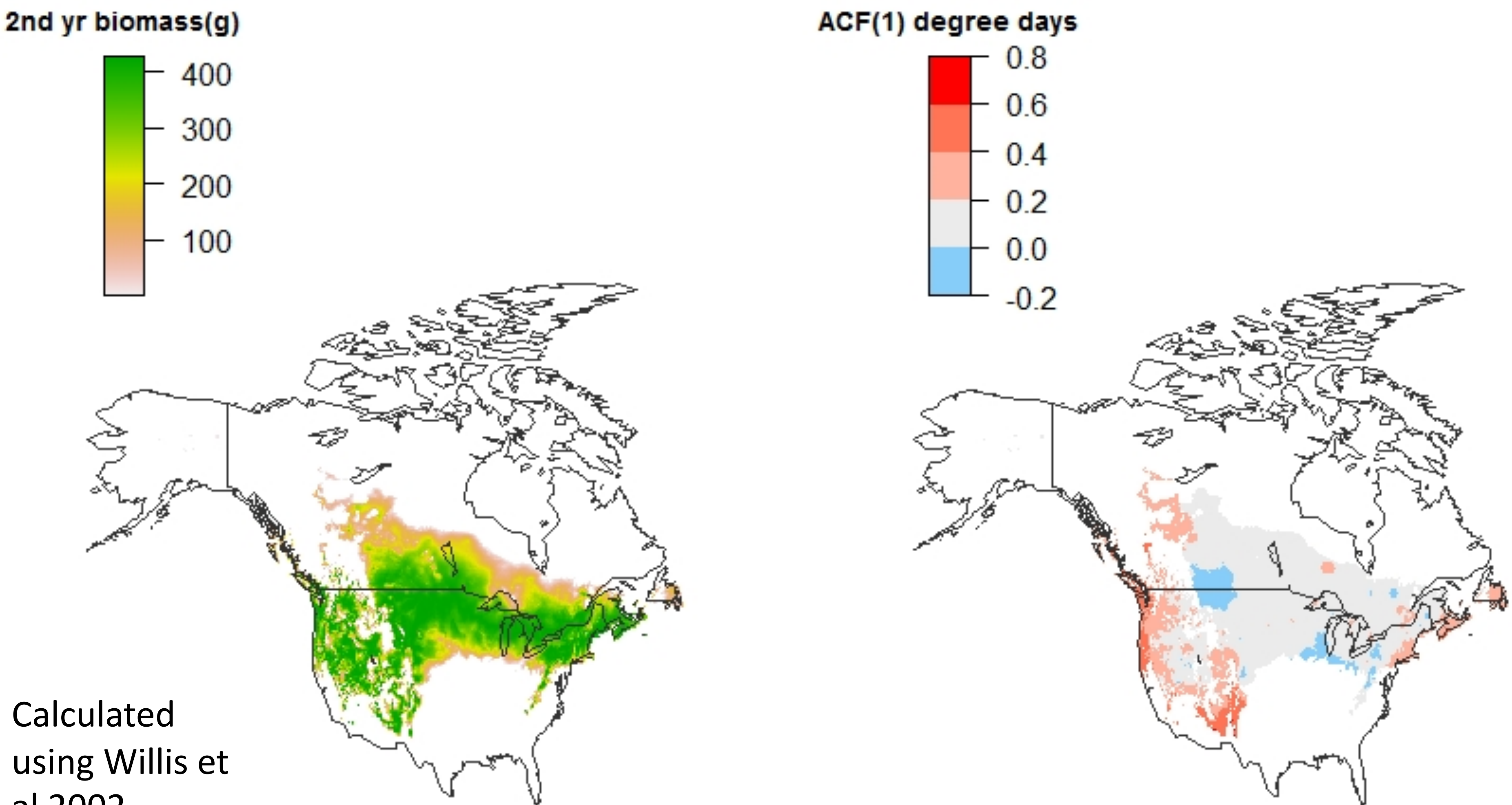


Dan Mckenney NRC Canada

Autocorrelation of growing degree days between years

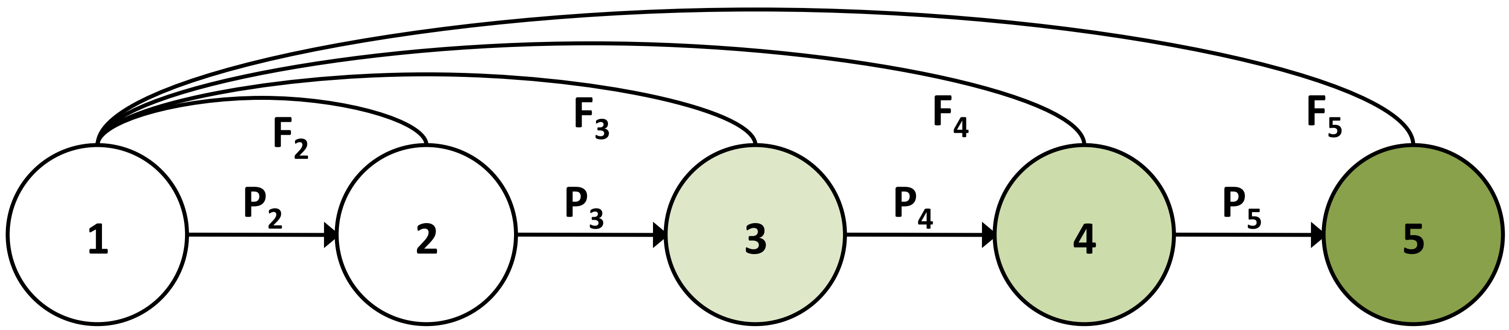


Two year predicted mean biomass accumulation and degree day ACF

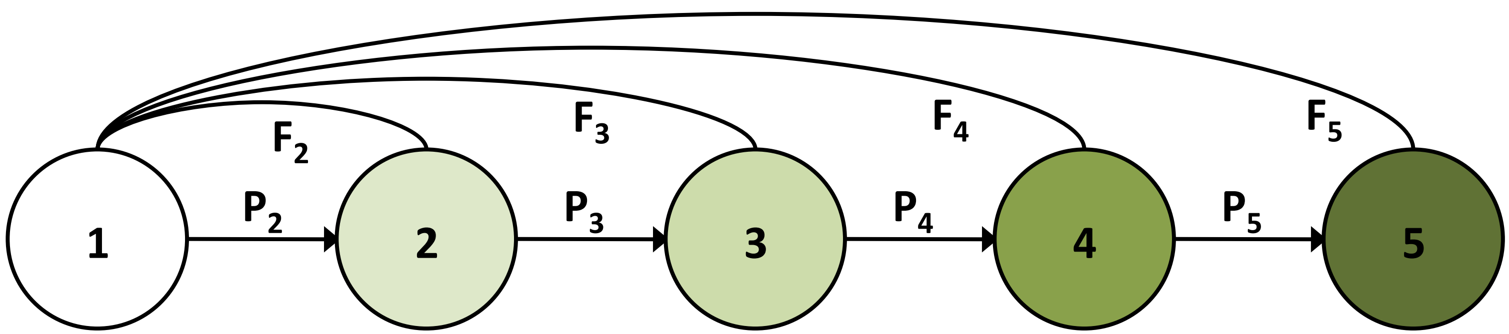


Calculated using Willis et al 2002

From cold to warm: Changing probability of flowering

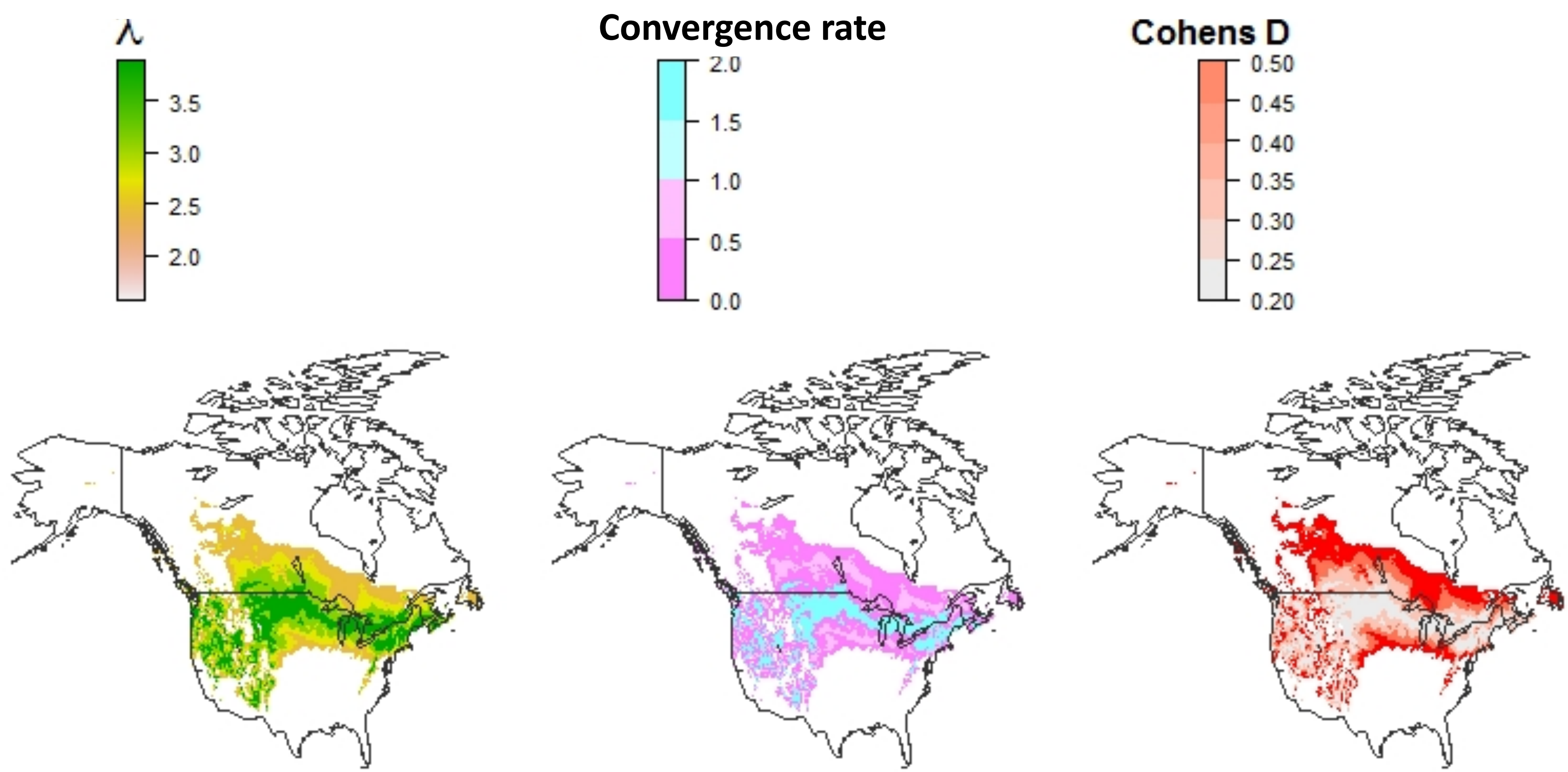


Cold regions



Warm regions

Where I would like to go: Mapping probability of transients!



Part 3.3: Conclusions

- Life history is different in areas with different climate
- Climate induced differences in life history and autocorrelated environmental variation lead to different potential risks
- Giant hogweed…. Preliminary, but forecast is not good

Warning: Canada's Most Dangerous Plant Has Been Spotted All Over Quebec

Keep yourself and your pets safe this summer!

Lena Slanisky · 1 month ago · Updated on May 31 @ 08:52 AM · 636

Overall:
Think about transients when you think about risk of invasive species impact

Risk of invasive species impact = Windows of opportunity

Desperately seeking…

- Grads that like to mix it up with data, stats and math (or even experiments)…

https://xkcd.com/1838/

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What's next?

- Part 1: What is autocorrelation in the underbark microclimate?
- Part 1: How do we better model spring and summer temperatures in the underbark microclimate?

What’s next?

- Part 2: What is the effect of environmental autocorrelation on the transient dynamics of stage-structured population models?
- Part 3: how do we link the probability distributions of thermal resposes to autocorrelated temperatures to structured population models